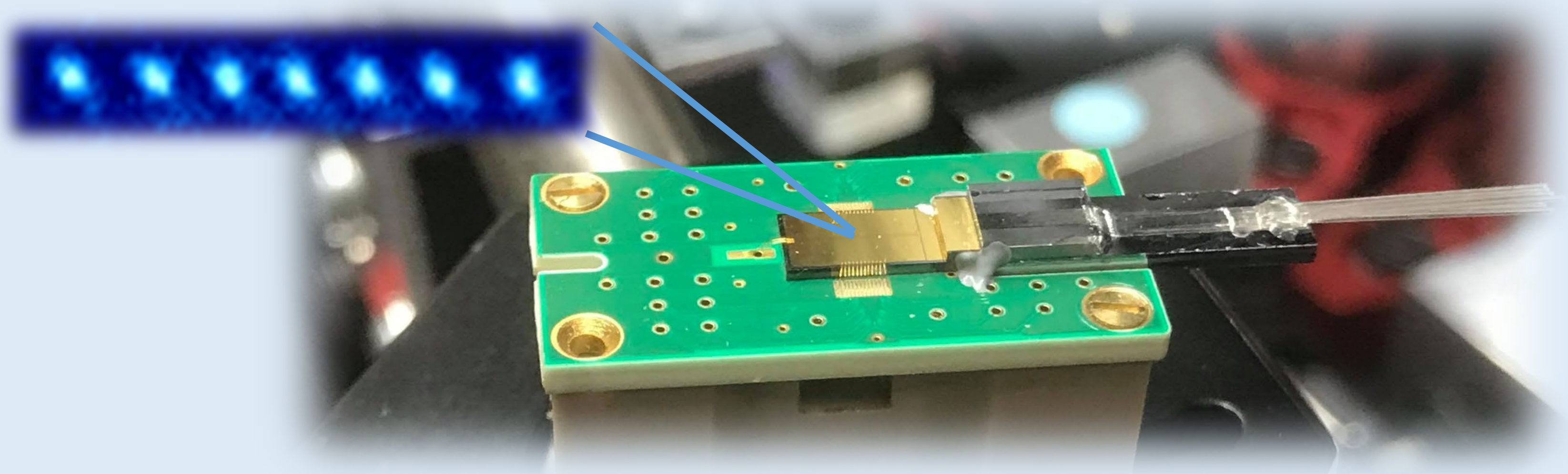
Quantum computing with trapped ions

Jonathan Home
Institute for Quantum Electronics, ETH Zürich



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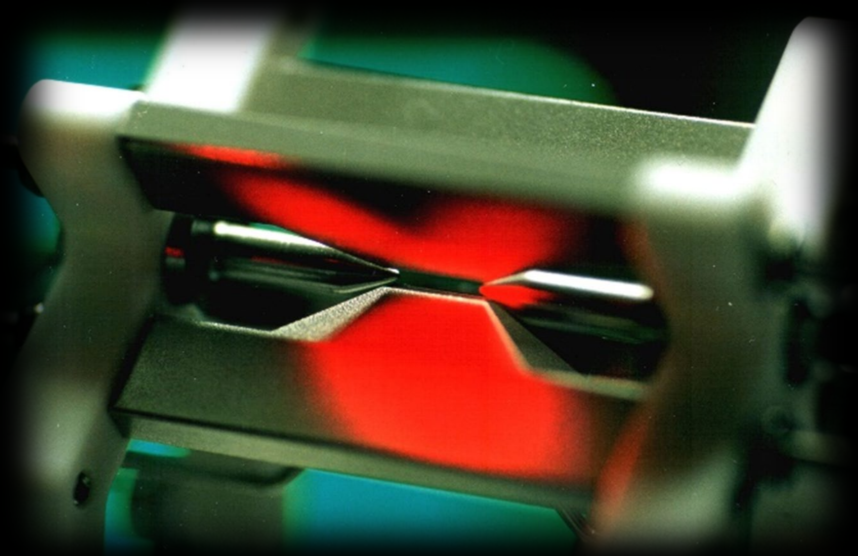
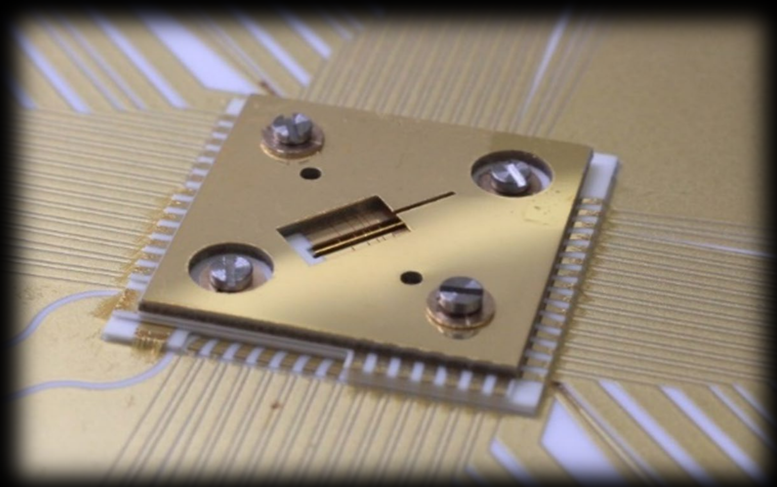
Trapped ions

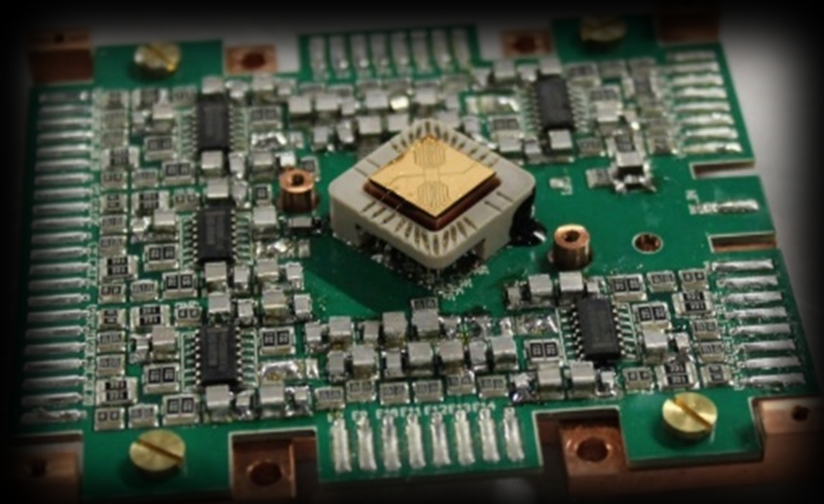


Room temperature

$$V_{\text{static}}(\mathbf{r}) + \Phi_{\text{RF}}(\mathbf{r})$$

Ponderomotive potential
(change of rapid kinetic motion with position)





4 Kelvin

Radio-frequency ion traps

Laplace's equation
– no chance to trap with static fields

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0$$

Paul trap: Use a ponderomotive potential – change potential fast compared to speed of ion

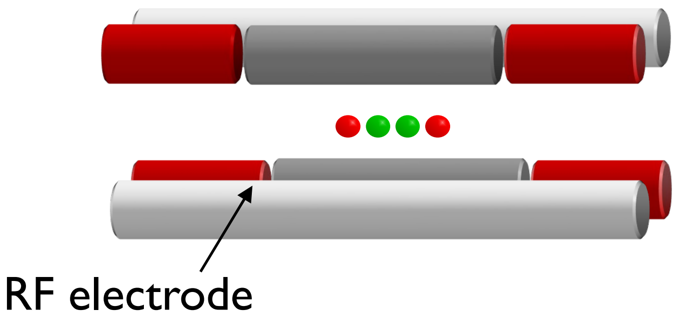
$$\frac{\partial^2 V}{\partial x^2} + \left(\frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}\right)\cos(\Omega t)$$

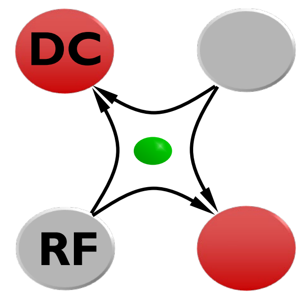
$$M\frac{d^2 x}{dt^2} = qE\cos\Omega t \qquad \frac{1}{2}M\left(\frac{dx}{dt}\right)^2 = U_{\mathrm{PP}} = \frac{q^2E^2}{2M\Omega^2}\sin^2\Omega t$$

Time average - Effective potential energy which is minimal at minimum *E*

Penning trap: Add a homogeneous magnetic field – overides the electric repulsion

The “workhorse” linear Paul trap





Trap Frequencies

Axial : < 3 MHz

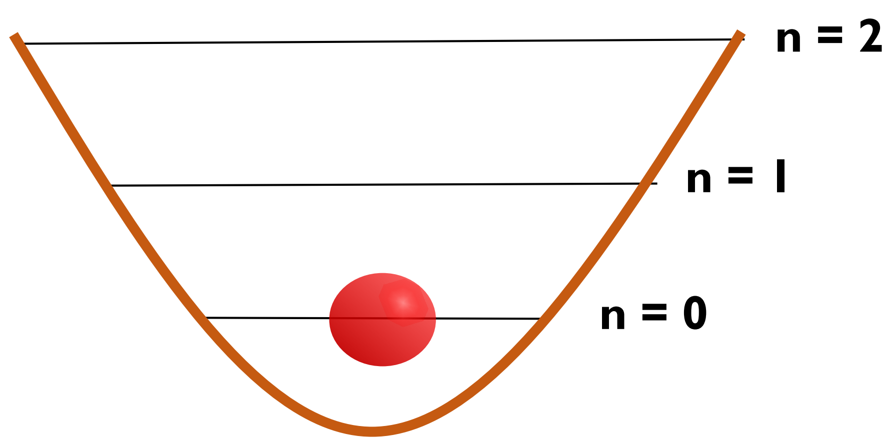
Radial: < 20 MHz

Radial Freq ✪ 1/Mass

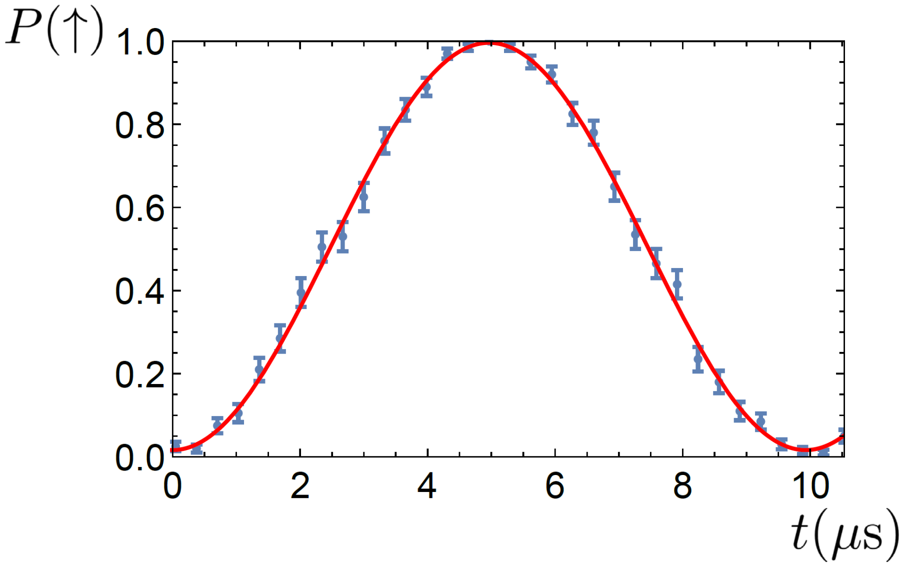
Potentials gives almost ideal harmonic behavior in 3D

Single ion

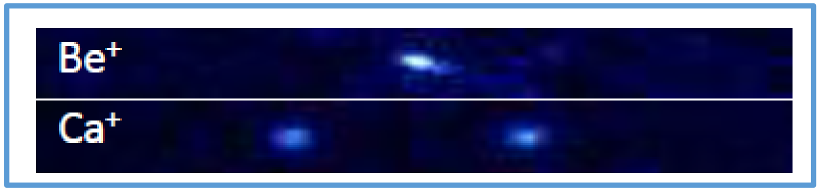
$$\hat{H} = \hbar\omega(\hat{a}^{\dagger}\hat{a} + 1/2)$$



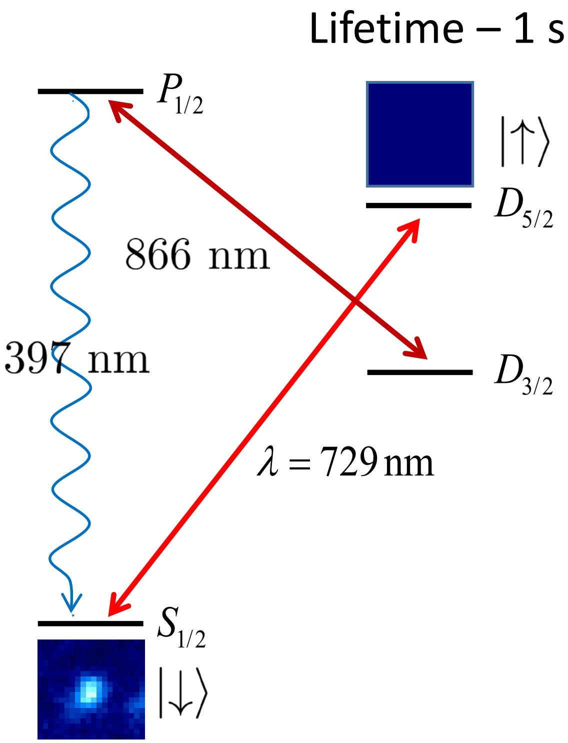
Internal state electronic qubits



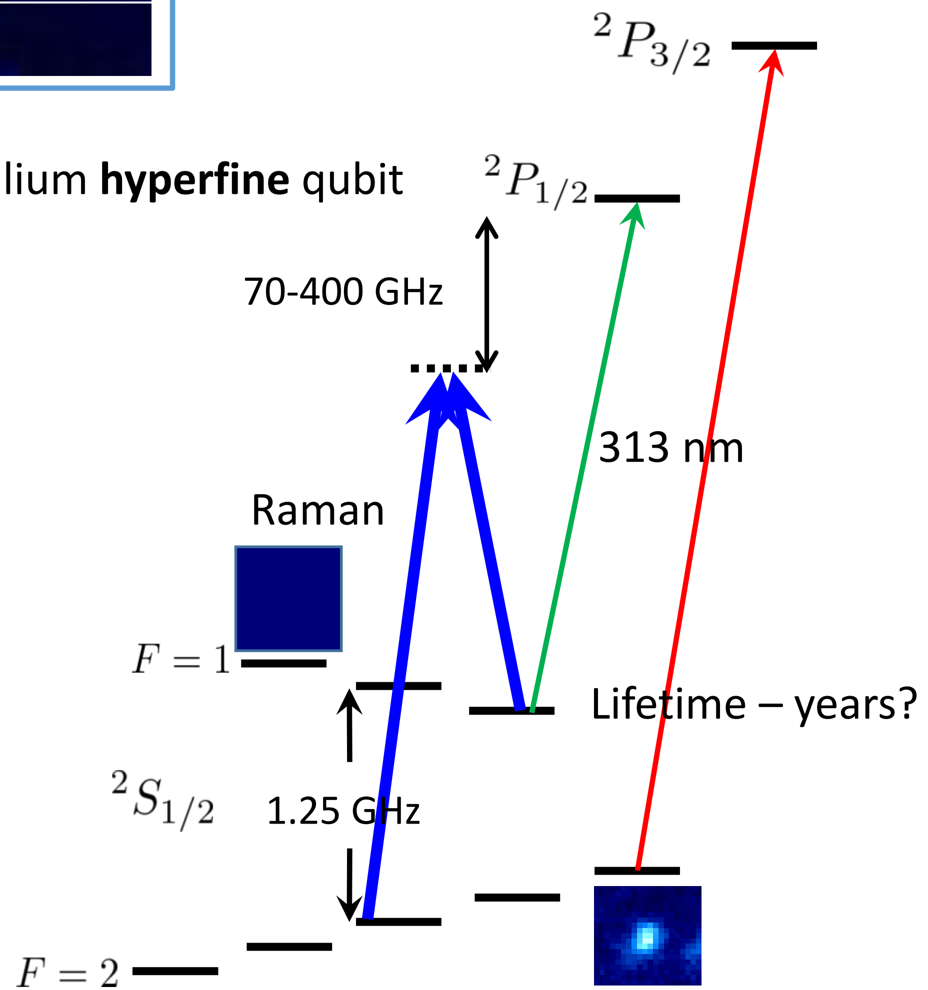
Qubit choices



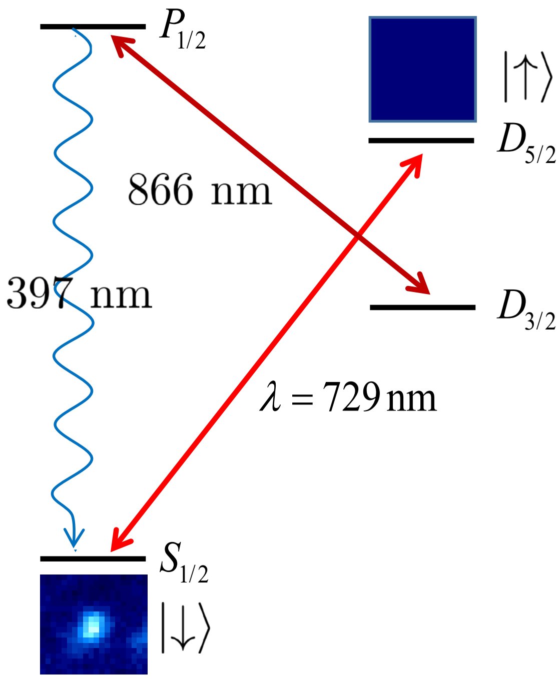
Calcium **optical** qubit



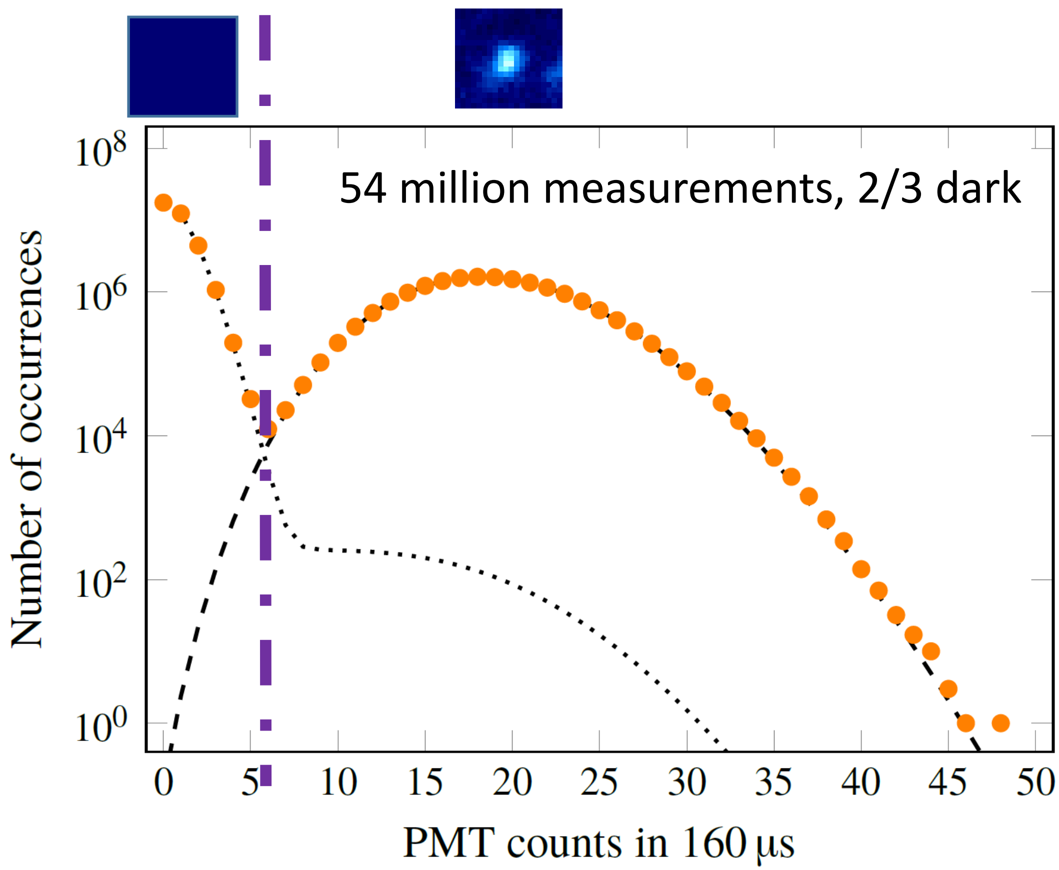
Beryllium **hyperfine** qubit



Qubit measurement



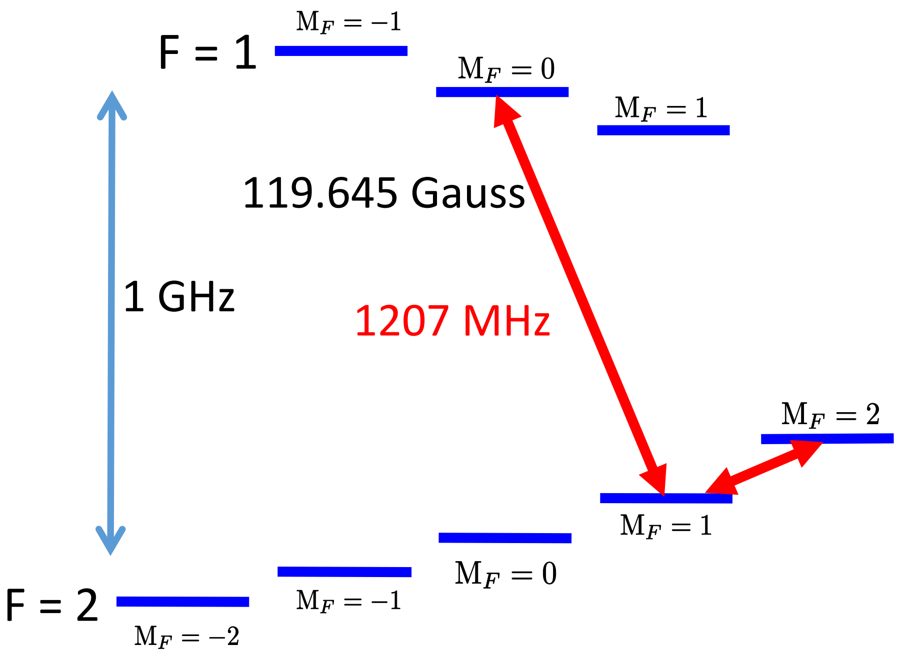
Threshold: 5.5 counts

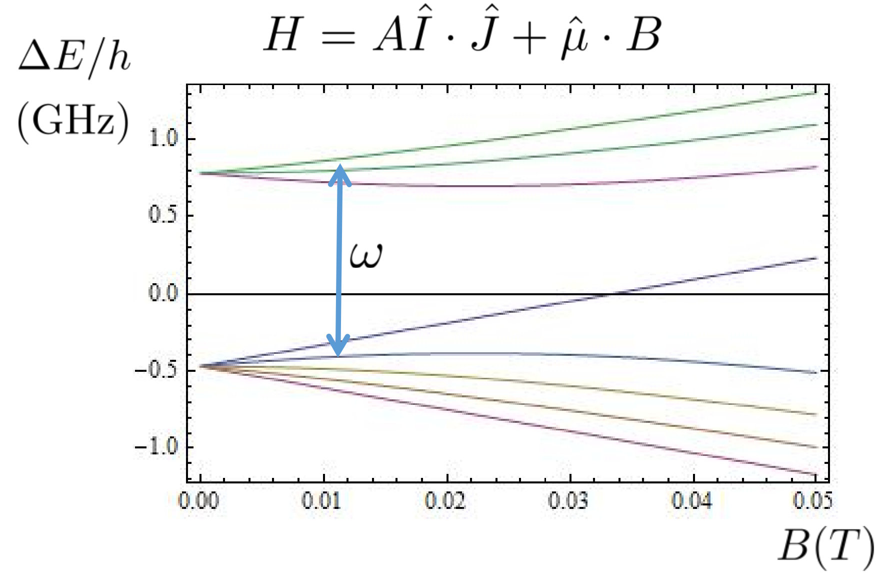


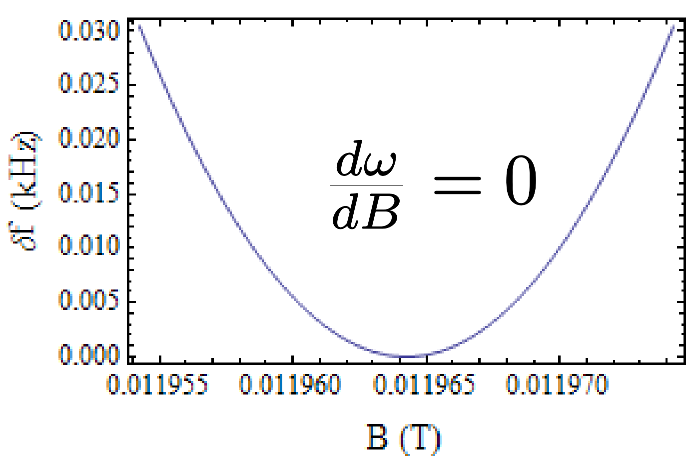
Single quantum system – many repeats
8,28,10,30,20,45,20 …. 35

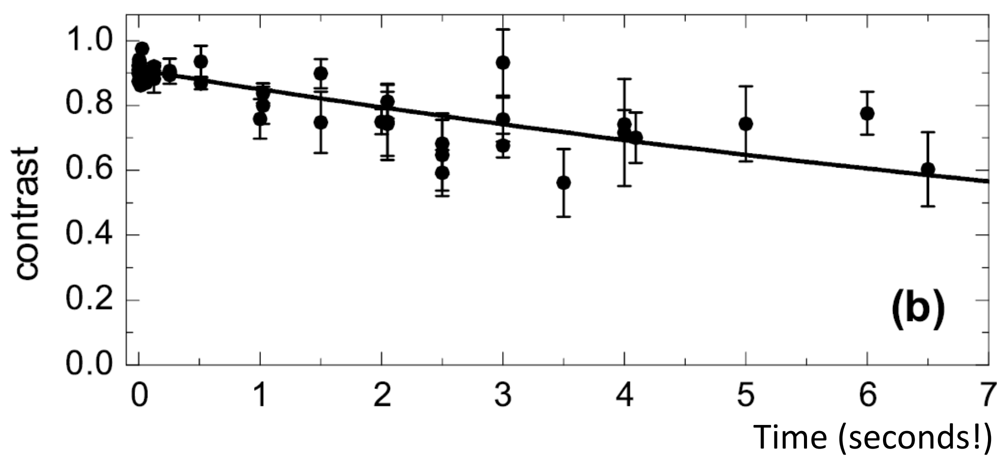
Single shot $p_{\mathrm{error}} = 2 \times 10^{-4}$

Field-independent “clock” qubits









Langer et al. PRL 95, 060502 (2005)

Identical qubits + Decoherence-Free Subspaces

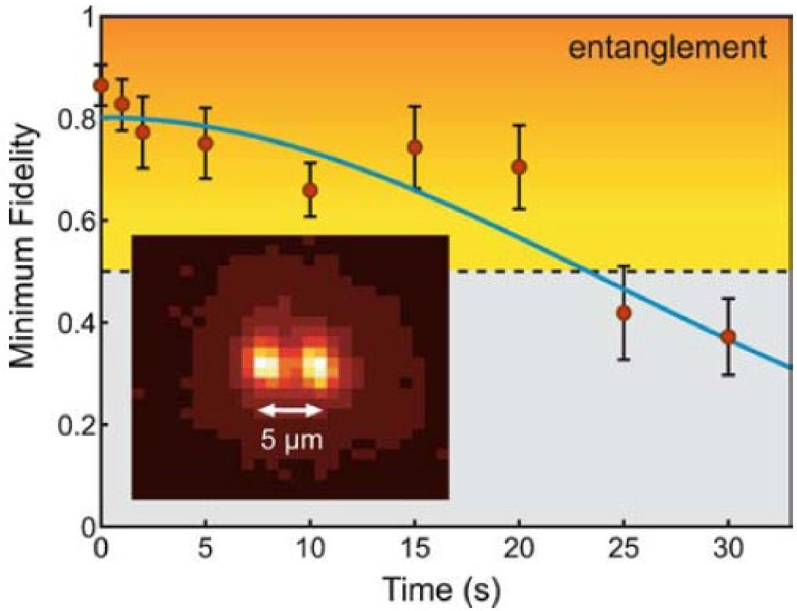
Rejection of common-mode noise – DFS states for identical qubits

$$|0\rangle + e^{i\omega'(t)t}|1\rangle \qquad\qquad |0\rangle + e^{i\omega(t)t}|1\rangle$$

Now consider entangled state

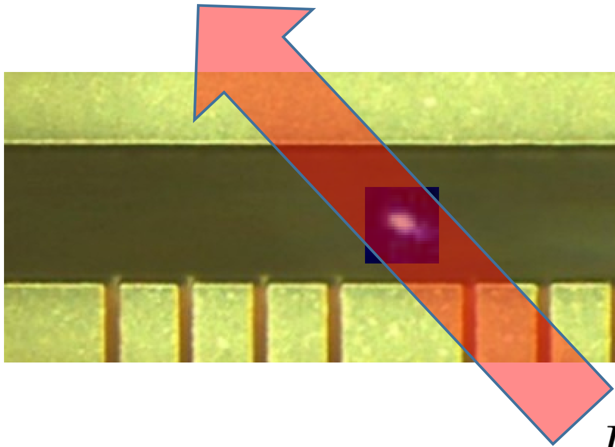
$$e^{i\omega(t)t}|01\rangle + e^{i\omega'(t)t}|10\rangle = e^{i\omega(t)t}\left(|01\rangle + e^{i(\omega'(t)-\omega(t))t}|10\rangle\right)$$

If noise is common mode, entangled states can have very long coherence times



Haffner et al., Appl. Phys. B 81, 151-153 (2005)

Single qubit gates – microwave or lasers



$I(t)$

$$\hat{H} = \begin{pmatrix} 0 & \Omega e^{i\phi} \\ \Omega e^{-i\phi} & 0 \end{pmatrix}$$

$$\hat{U}(t) = \cos(\theta/2)I + i\sin(\theta/2)\sigma_x$$

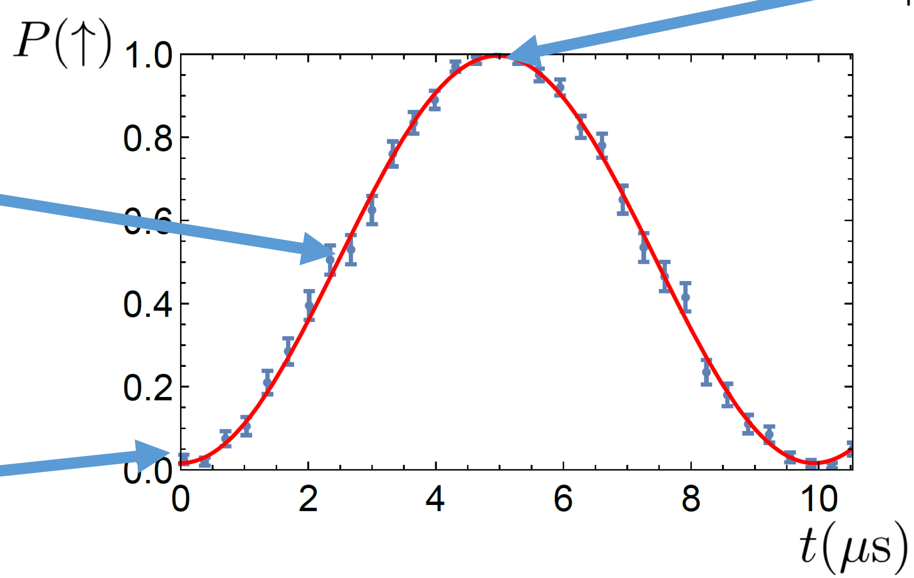
$$\theta = \Omega t$$

$|\uparrow\rangle$ “Pi” pulse

“Pi by two” pulse

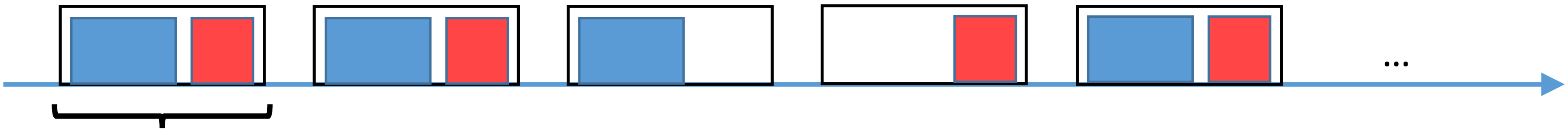
$$\frac{1}{\sqrt{2}}\left(|\uparrow\rangle + e^{i\phi}|\downarrow\rangle\right)$$

$|\downarrow\rangle$

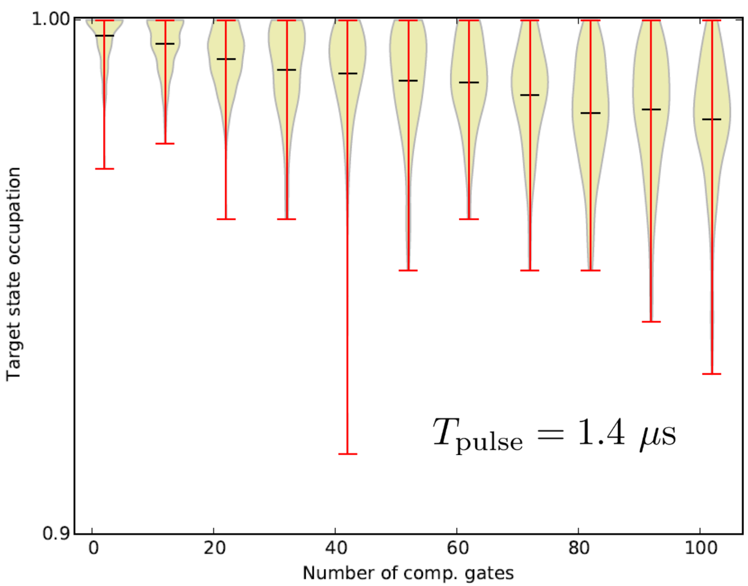


High fidelity single qubit gates

Method: Randomized benchmarking: long sequences of randomly chosen (known) operations



Computational gate = $\hat{R}_j(\pi).\hat{R}_i(\pi/2) \quad i,j = \pm\hat{X}, \pm\hat{Y}, \pm\hat{Z}, \hat{I}$



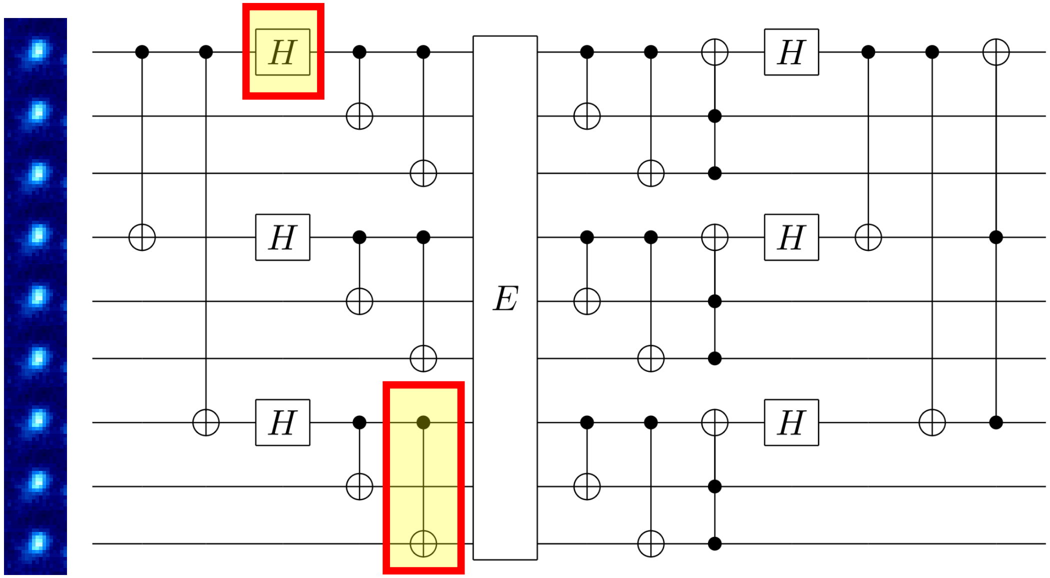
Average error **> 99.98%** per computational gate

Highest fidelity operations: 0.999999 (Oxford, microwave drive)

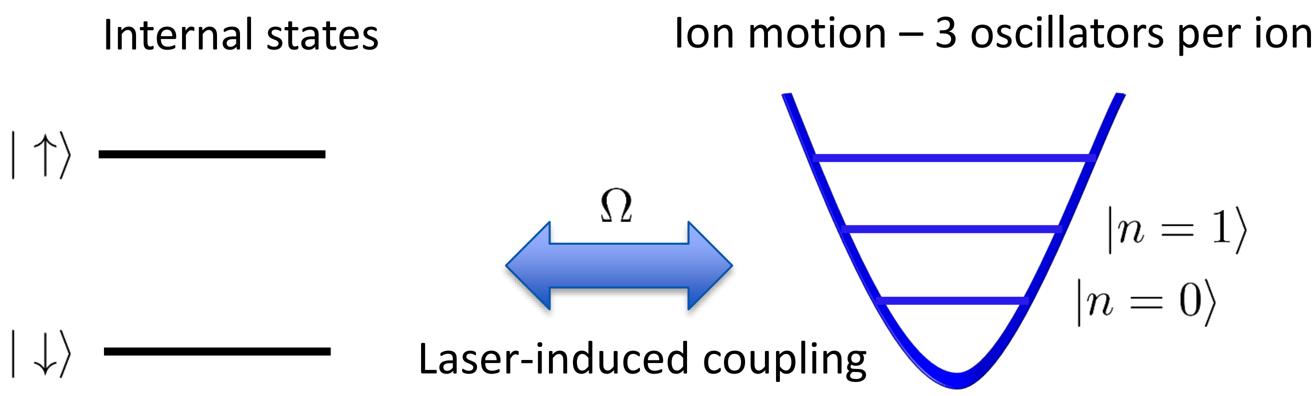
Spin-spin interactions + multi-qubit gates

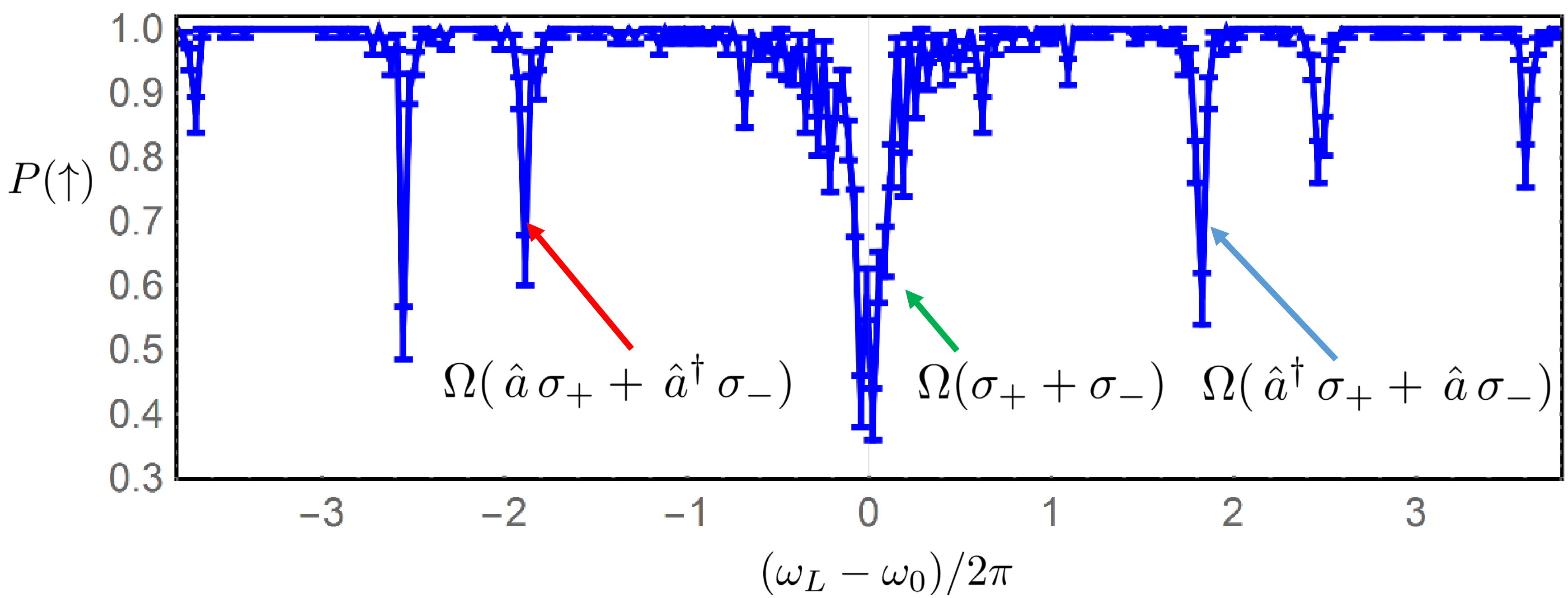
Realize circuits with ***many*** qubits

1 x Logical qubit $|0\rangle_q, |1\rangle_q$



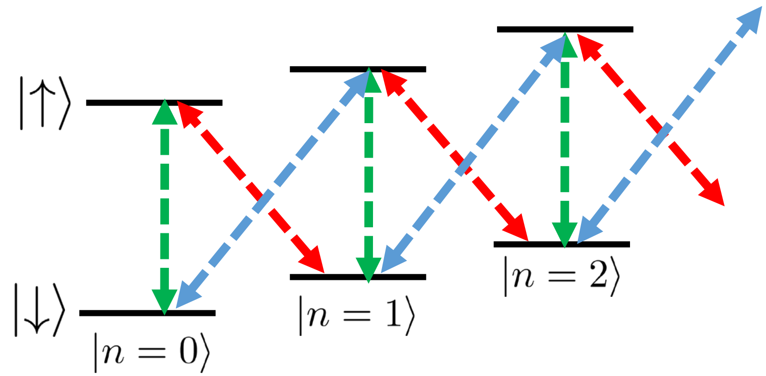
Parametrically coupled spin-oscillator system

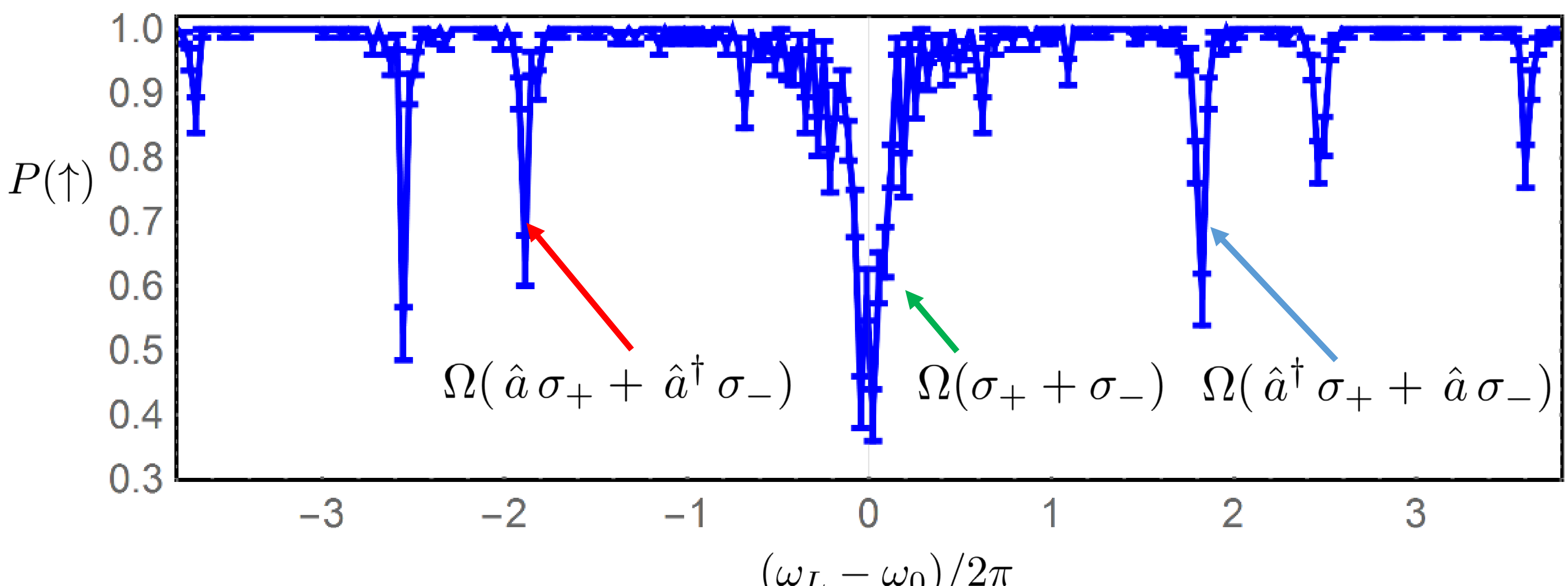




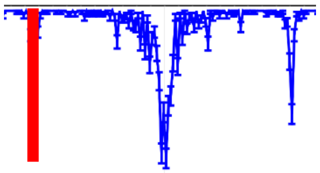
Choice of Hamiltonian

Laser frequency picks out resonant Hamiltonian



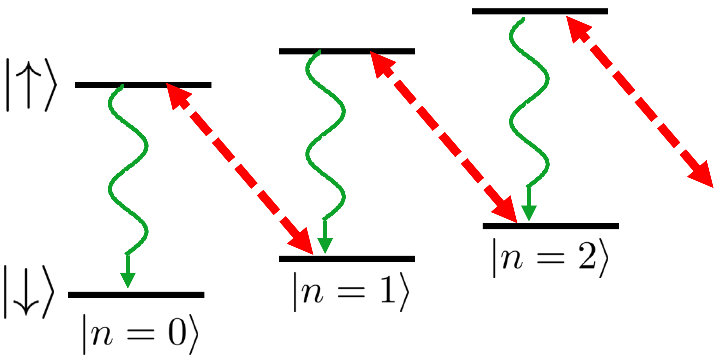


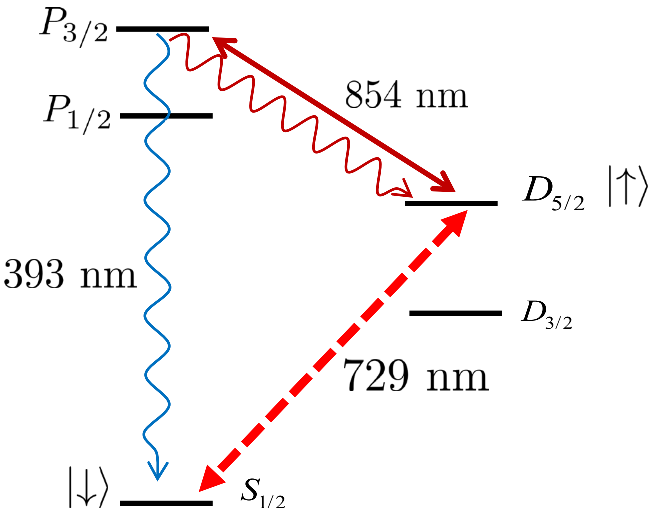
Ground state laser cooling

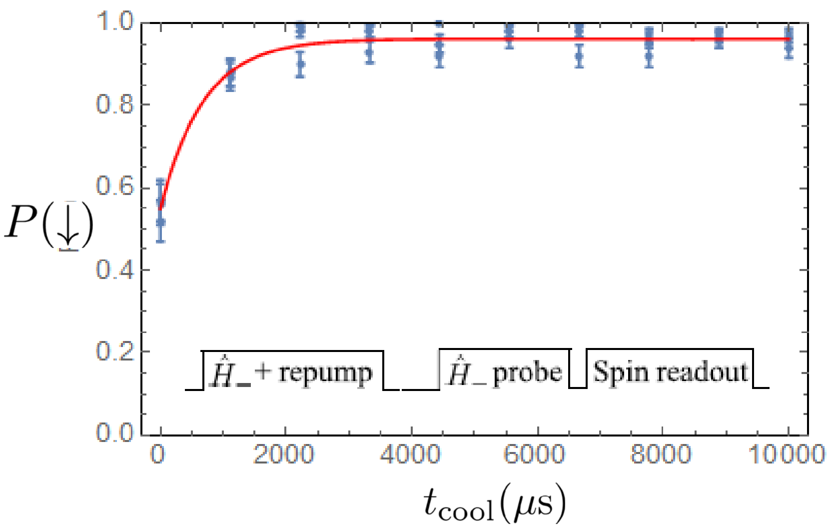


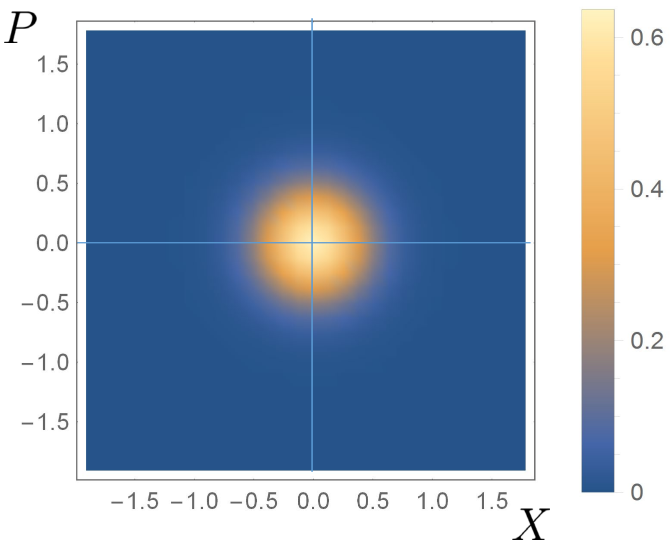
Monroe et al. PRL 75, 4011 (1995), Meekhof et al. PRL 76, 1796 (1996)

$$\hat{H}_r = \Omega(\hat{a}\,\sigma_+ + \hat{a}^\dagger\,\sigma_-)$$

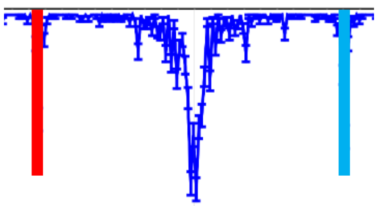








Optical state-dependent force

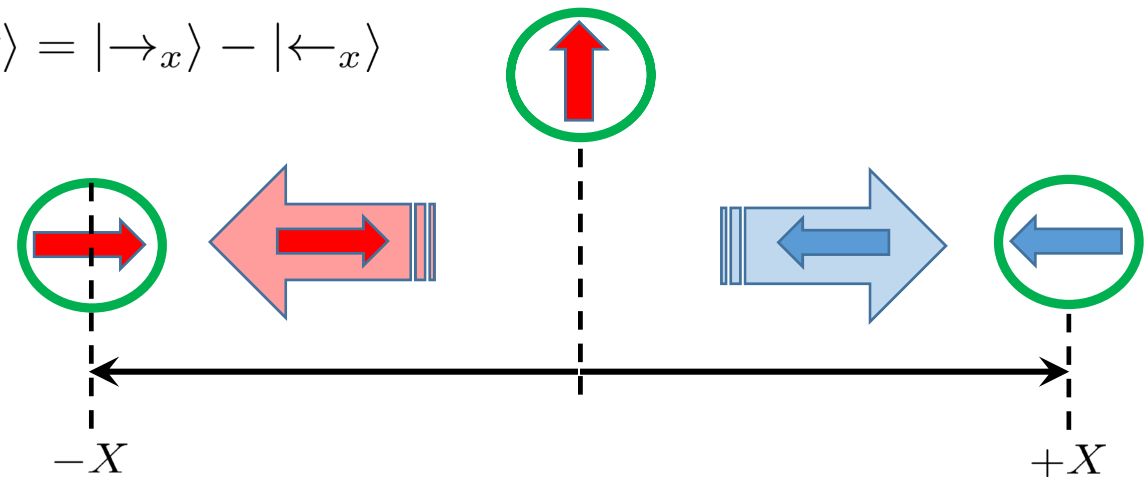


Equally driven resonant sidebands

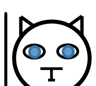
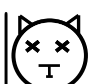
$$\hat{H}_I = F_0 \left(\hat{a}^\dagger + \hat{a} \right) \sigma_x = F_0 X \sigma_x$$

$$U(t) = e^{-i \frac{F_0 t}{\hbar} X \sigma_x} = D(\alpha_X(t) \sigma_x)$$

Before $|\uparrow\rangle = |\rightarrow_x\rangle - |\leftarrow_x\rangle$

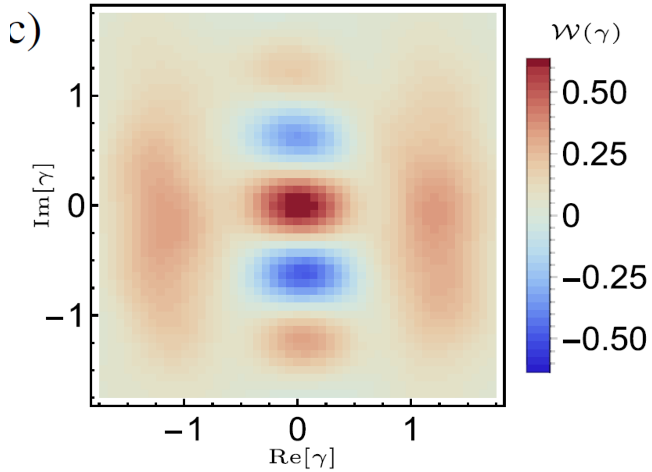


After $|\rightarrow\rangle\, |-\alpha_X\rangle + |\leftarrow\rangle\, |+\alpha_X\rangle$

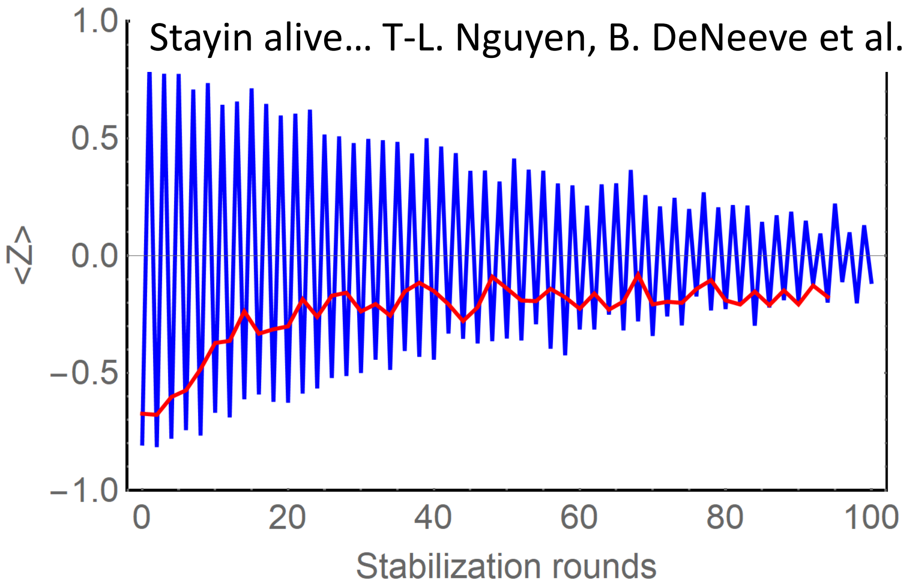
$|\rightarrow\rangle$ |  $\rangle$ + $|\leftarrow\rangle$ |  $\rangle$

Cats which are squeezed, dead alive and in purgatory

C. Flühmann et al. PRL 125, 043602 (2020)

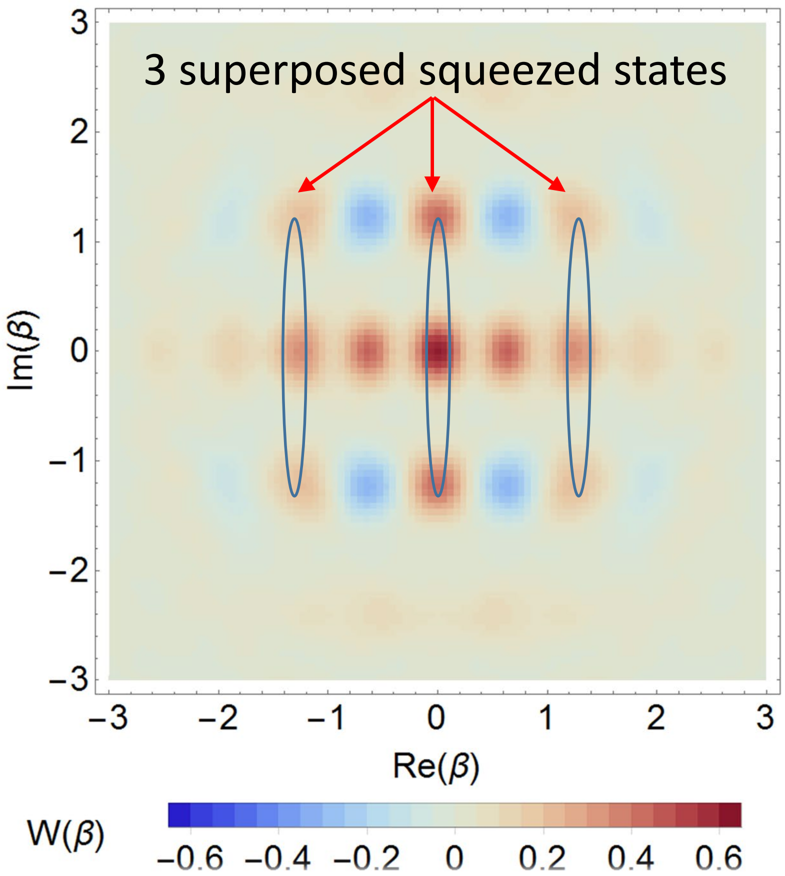


Stayin alive... T-L. Nguyen, B. DeNeeve et al.

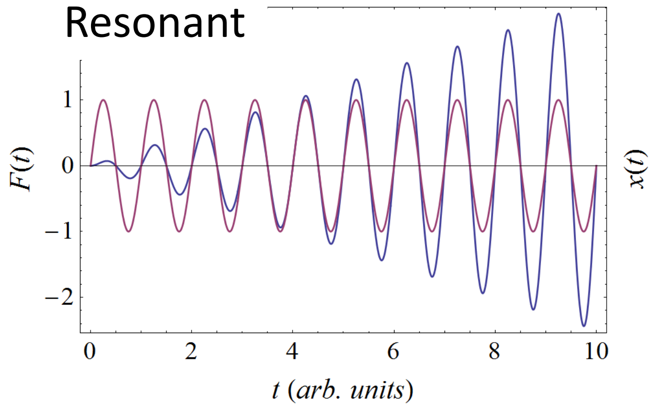


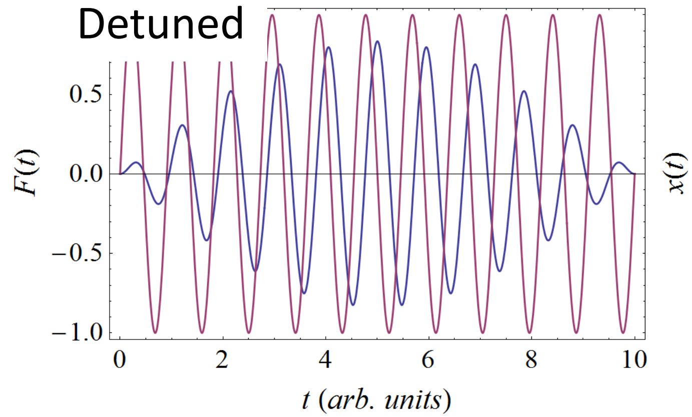
A quantum error-correction code

C. Flühmann et al. Nature 556, 513 (2019)



The forced harmonic oscillator





"returns" after

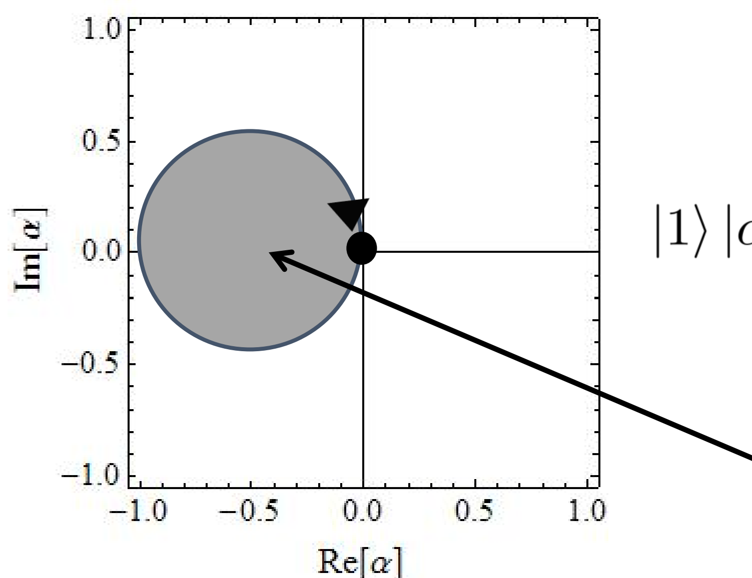
$$t = \frac{2\pi}{\delta}$$

Excitation amount

$$\propto \frac{F}{\delta}$$

Evolution $$U = \exp\left(\frac{i}{\hbar}\int^{t} H(t')dt' - \frac{1}{2\hbar^2}\int^{t}\int^{t'} \underline{[H(t'),H(t'')]}dt'dt'' + \ldots\right)$$

Transient excitation,
phase acquired

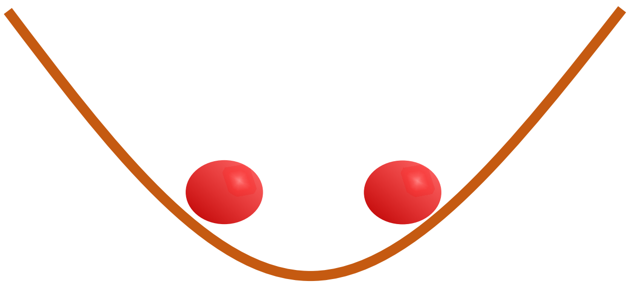


$$|1\rangle\,|\alpha_0\rangle \rightarrow e^{i\Phi}\,|1\rangle\,|\alpha_0\rangle$$

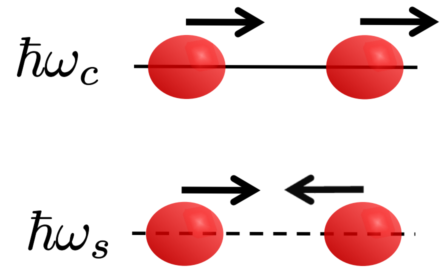
$$\Phi \propto A$$

State dependence and normal modes

$$V = \frac{k}{2} z_1^2 + \frac{k}{2} z_2^2 + \frac{q^2}{4\pi\epsilon_0 |z_1 - z_2|}$$

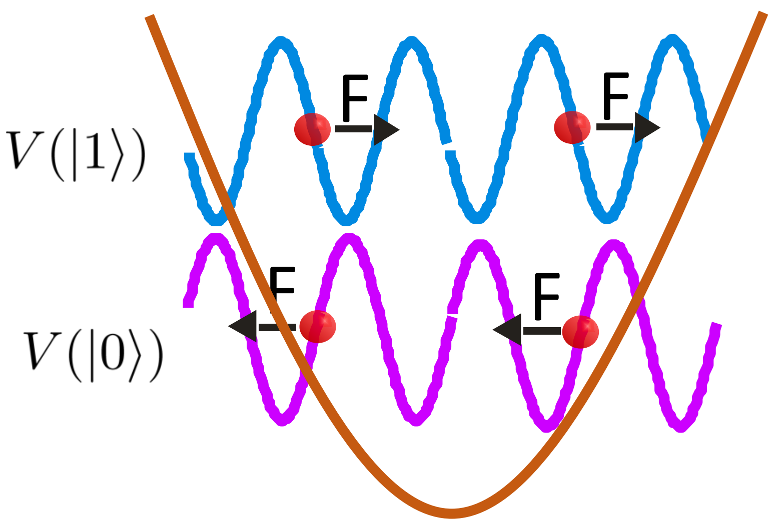


Independent normal mode oscillations
- shared motion



Stretch mode

Oscillating force close to resonance with **Stretch mode** of motion

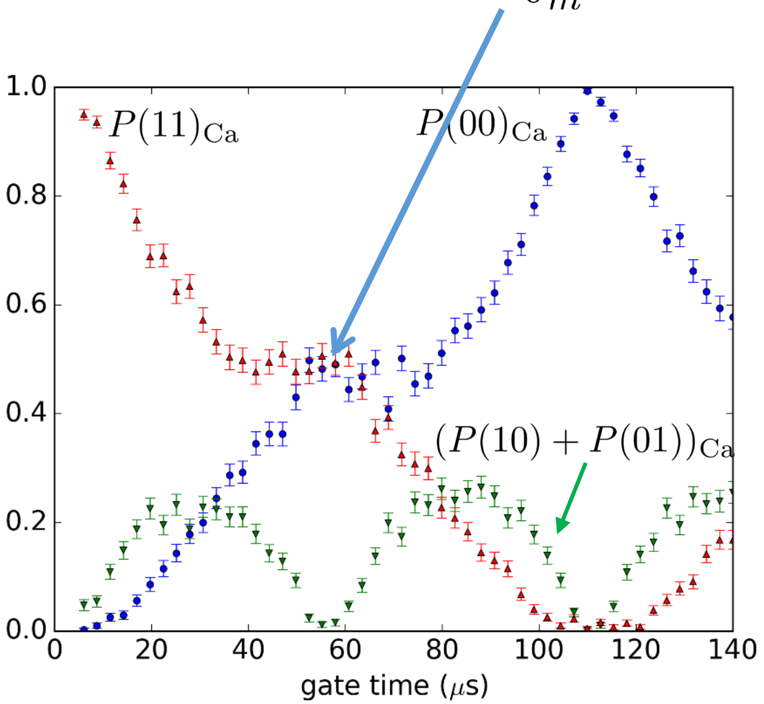


$\|1\rangle\|1\rangle$	No Motion = no phase
$\|1\rangle\|0\rangle$	Motion = phase
$\|0\rangle\|1\rangle$	Motion = phase
$\|0\rangle\|0\rangle$	No Motion = no phase

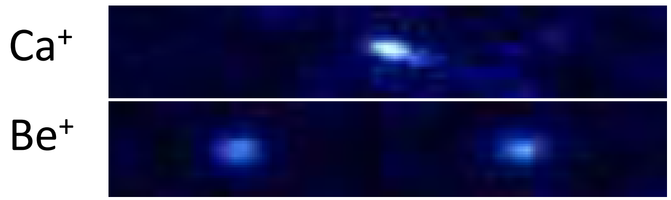
Gate time dynamics – 2 and 3 ions

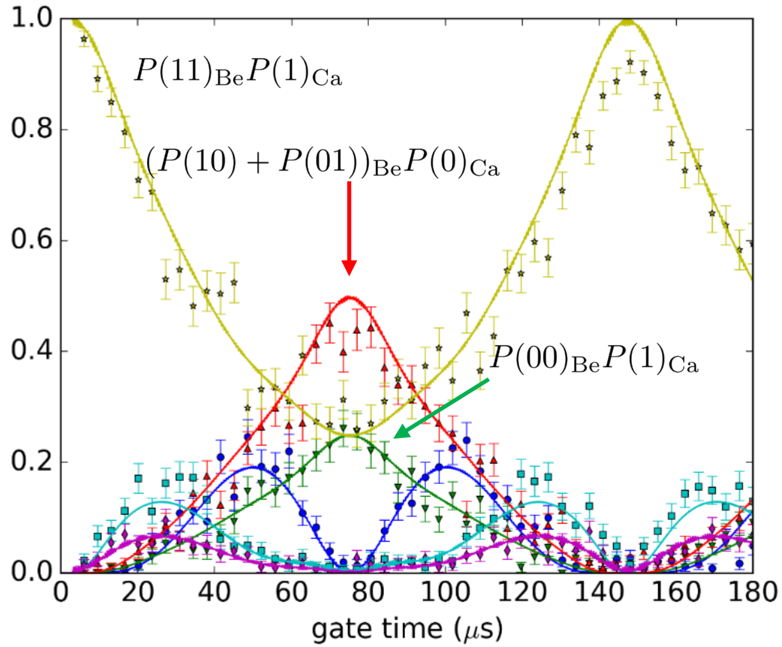
$$U(t) = D\left(\alpha(t)\hat{S}_x\right) e^{i\Phi(t)\hat{S}_x^2}$$

2 ions, 1 or 2 species $t = \frac{2\pi}{\delta_m}, \alpha(t) = 0$



3 ions, 2 species





Gate fidelities ~99 % (Be or Ca or both)

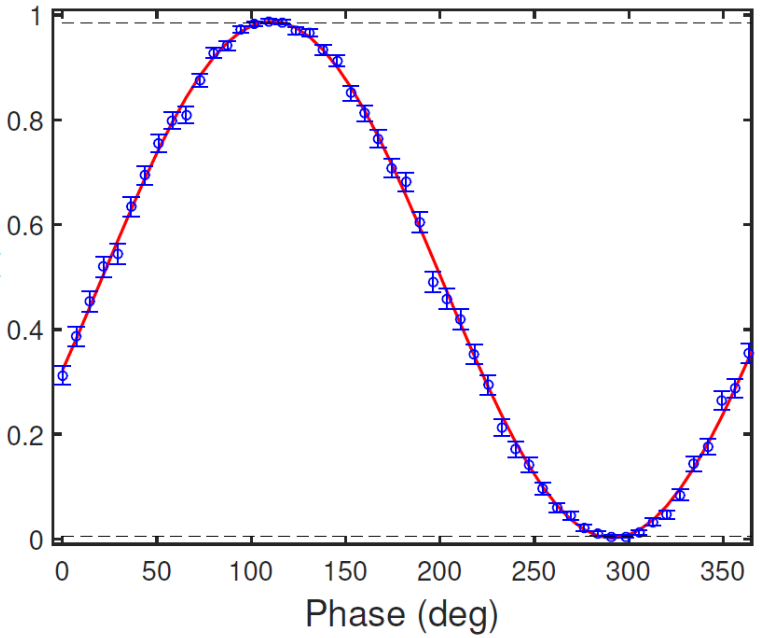
GHZ fidelity > 90%
(technical errors dominate)

Entangled state diagnosis

One ion interference experiment

$$\frac{1}{\sqrt{2}}\left(|0\rangle + ie^{i\phi}\,|1\rangle\right)$$

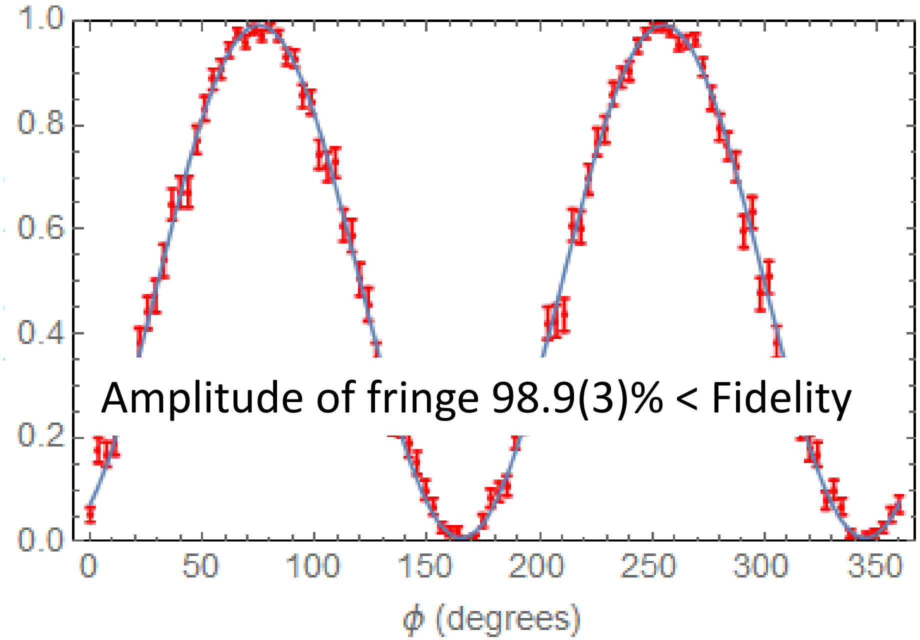
$$P(+_{\phi_{\pi/2}}) = \left(1 + \cos(\phi - \phi_{\pi/2})\right)/2$$



Entangled ions interference experiment

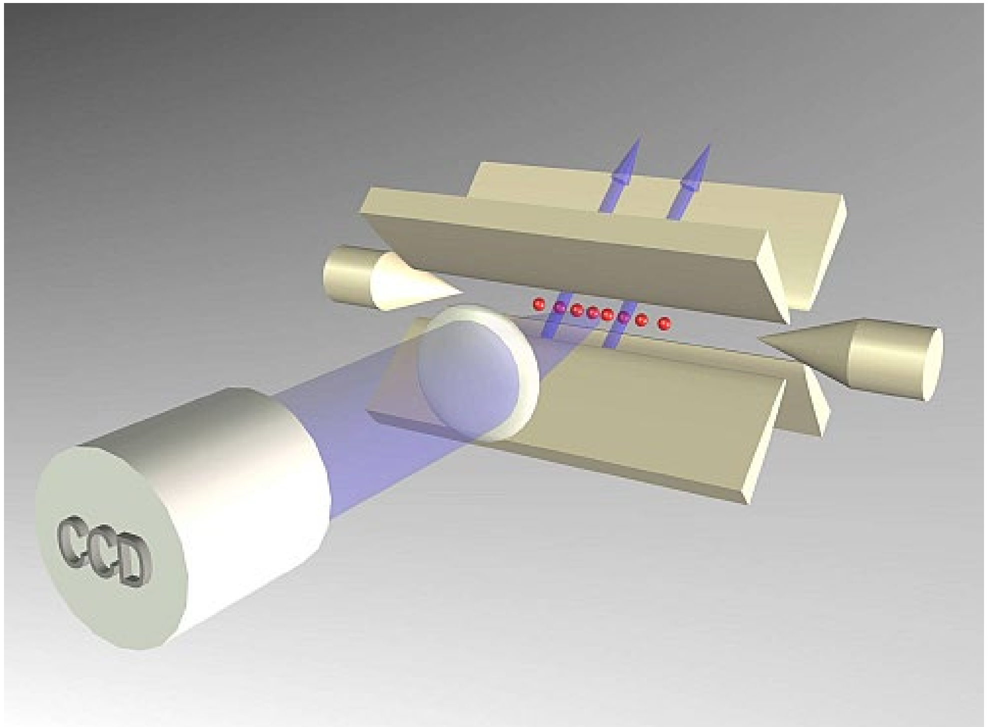
$$|\psi_+\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + ie^{2i\phi}\,|11\rangle\right)$$

$$P(11) + P(00) = \left(1 - \cos(2(\phi - \phi_{\pi/2})\right)/2$$



Best results worldwide:
Bell state F = 99.9% (Oxford, NIST, hyperfine)
Bell state F = 99.8% (Innsbruck, optical)

"Linear chain" Trapped-Ion Quantum Computing



Arbitrary single qubit gates

$$U(\theta) = e^{i\theta\sigma_\alpha^{(i)}}$$

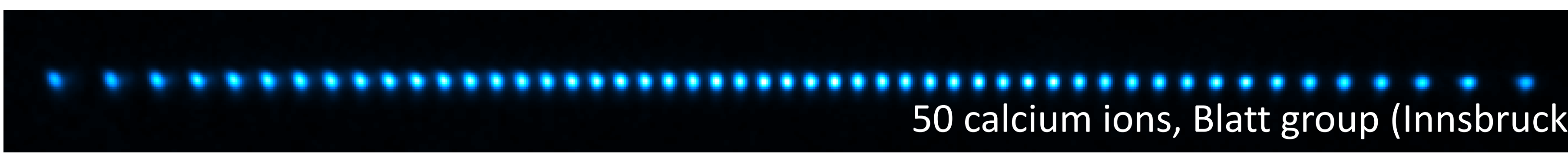
$$\sigma_\alpha^{(i)} = \sigma_X^{(i)}, \sigma_Y^{(i)}, \sigma_Z^{(i)}$$

Multi-qubit gates

$$U_{\mathrm{MS}}(\theta) = e^{i\theta S_X^2}$$

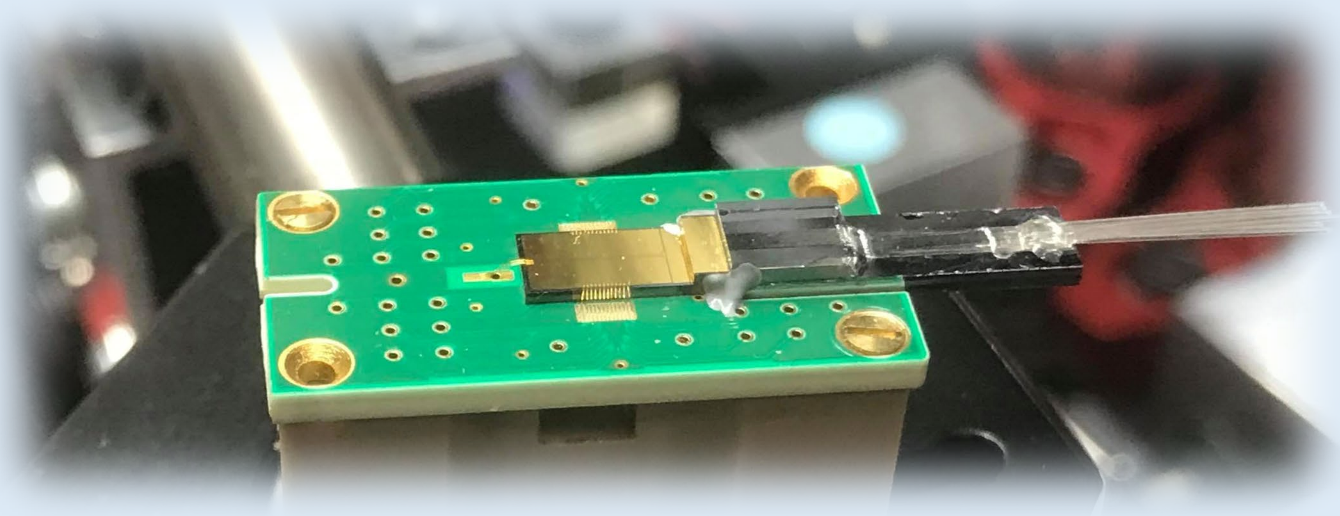
$$S_X = \sum_i^{N'} \sigma_X^{(i)}$$

Ion chain is rigid – all ions can be coupled

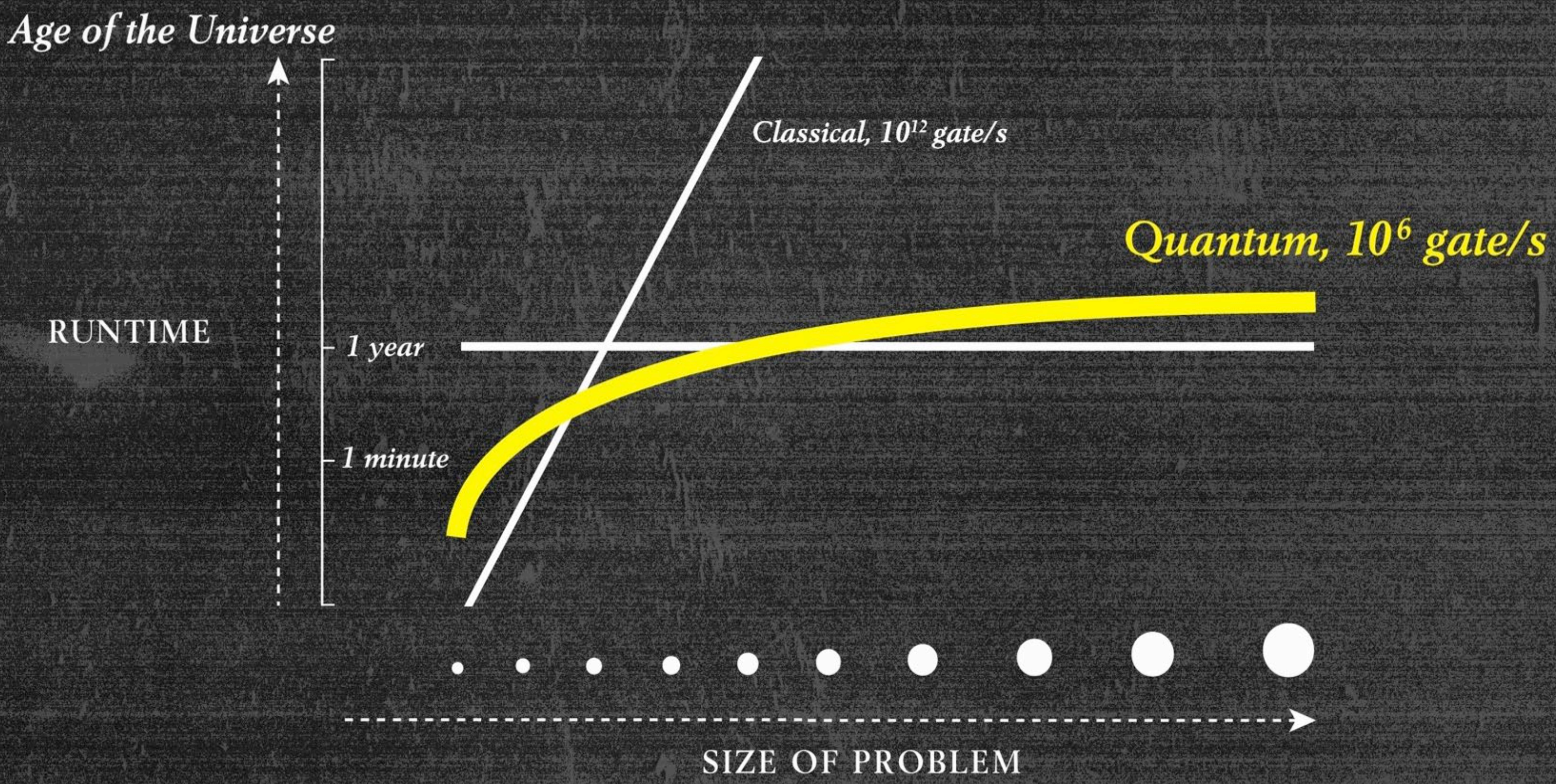


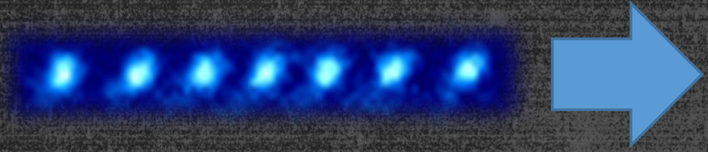
Most "scalable" approach for near-term NISQ: Monroe + IonQ, Blatt + AQT, etc.

Approaches to scaling



Quantum computers



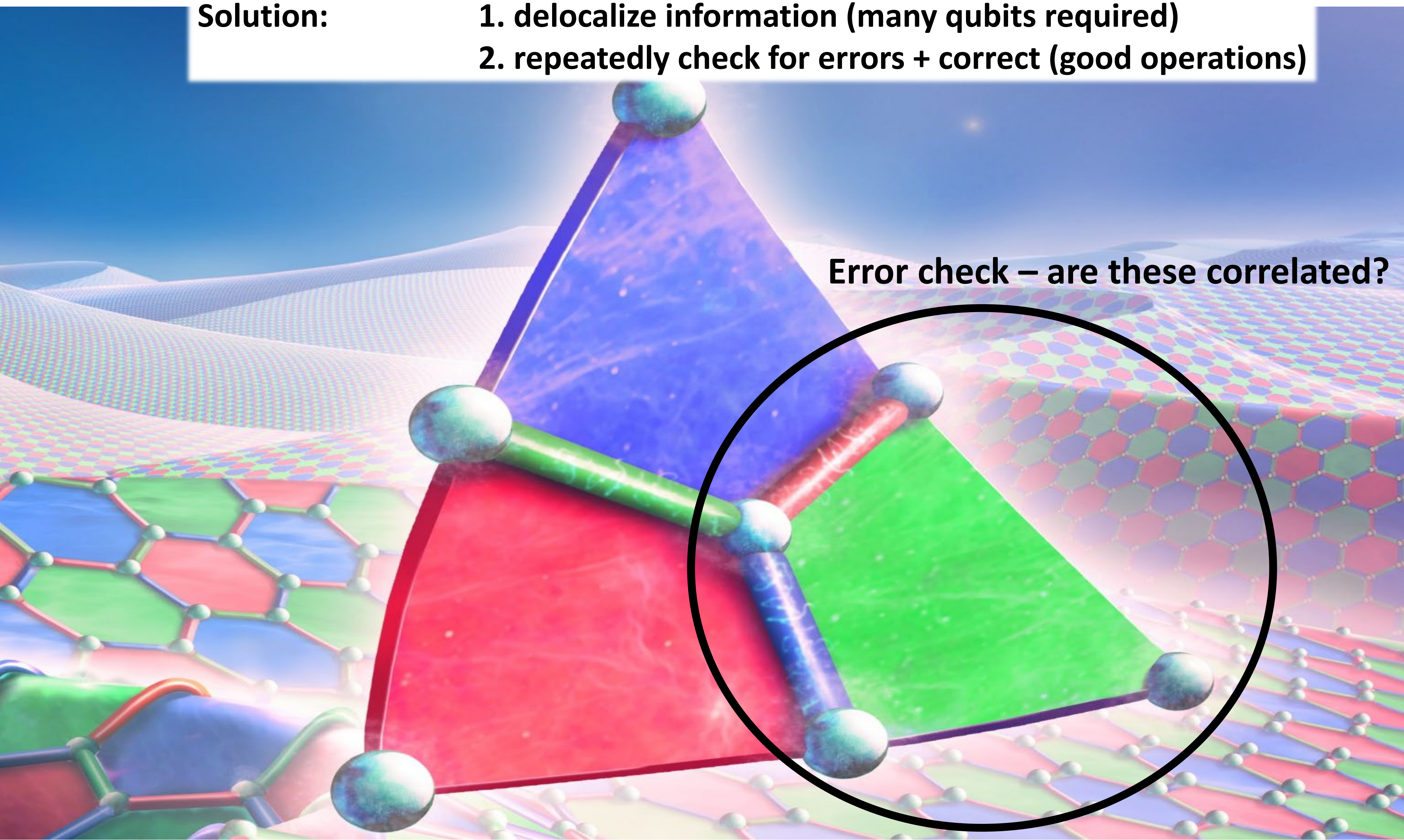


1 million qubits
10^{17} gates

Quantum error correction

Main observation: errors (physics) are mostly local

Solution:
1. delocalize information (many qubits required)
2. repeatedly check for errors + correct (good operations)



Scaling path for ion trap QIP

< 100 ions

Extended ion chains

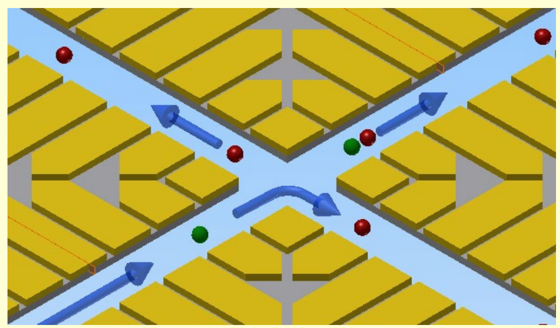
Gate fidelity/speed limits applications

Error-correction?

Intrinsically non-local, hard to be Fault Tolerant

100-200 ions

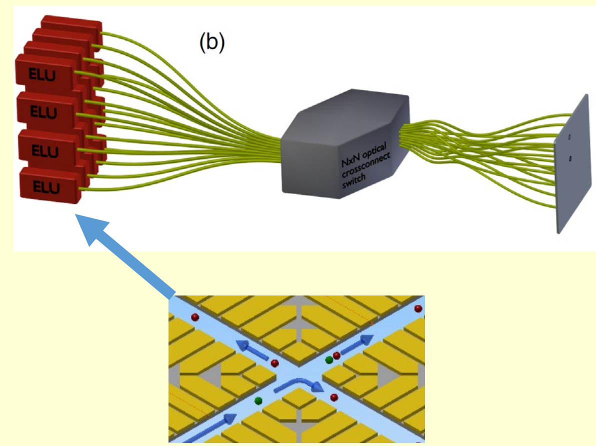
Quantum CCD
- Shuttle ions and isolate small numbers
- Parallel zone operation



Challenges:
Multi-channels of…
optical integration/delivery
Electrical wiring/fabrication

> 200 ions

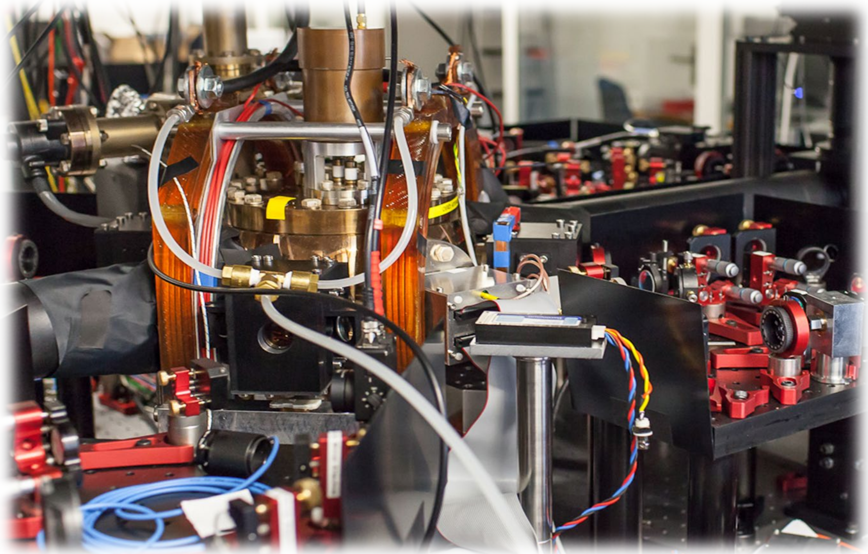
Photonic links

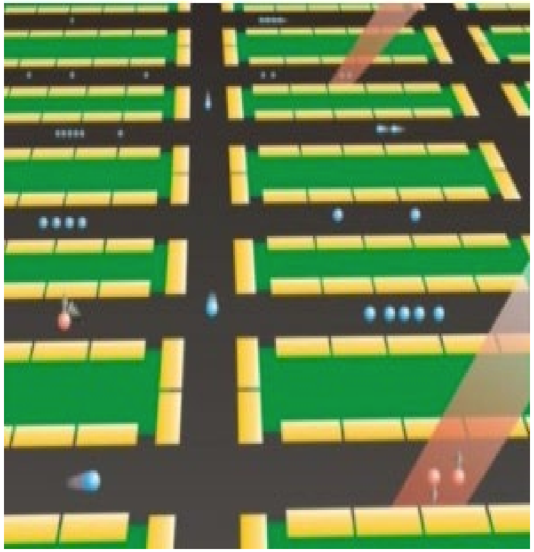


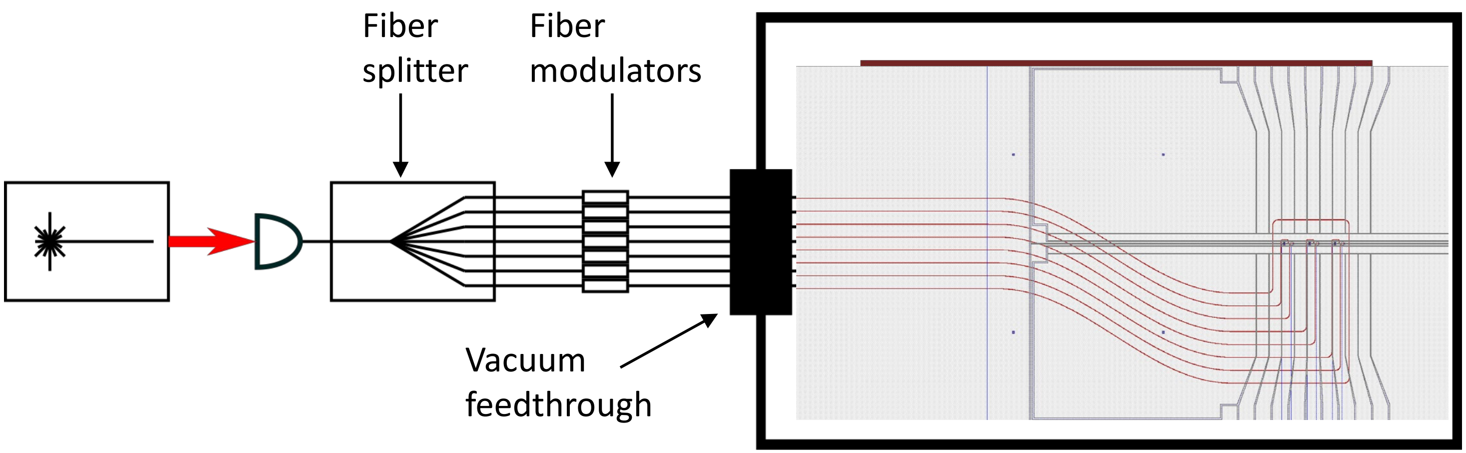
Rate:

How to integrate optical cavities

Optical wiring of the quantum computer







- MIT + Lincoln labs: K. Mehta et al. Nature Nano 11 1066 (2016), Challenge: 33 dB loss from input to ion
- R. J. Niffenegger *et al*, arXiv 2001.05052 (2020): Delivery near UV and visible light to ions

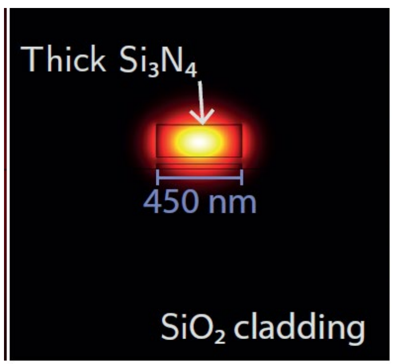
Trap-integrated waveguides

K. Mehta et al. arXiv:2002.03358 (2020)

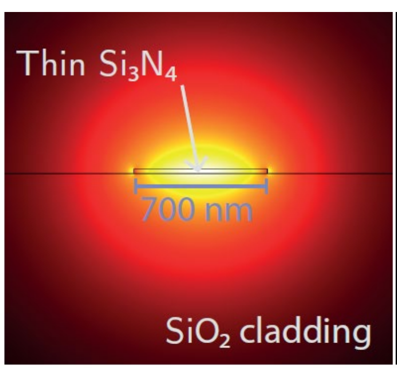
Commercial foundry

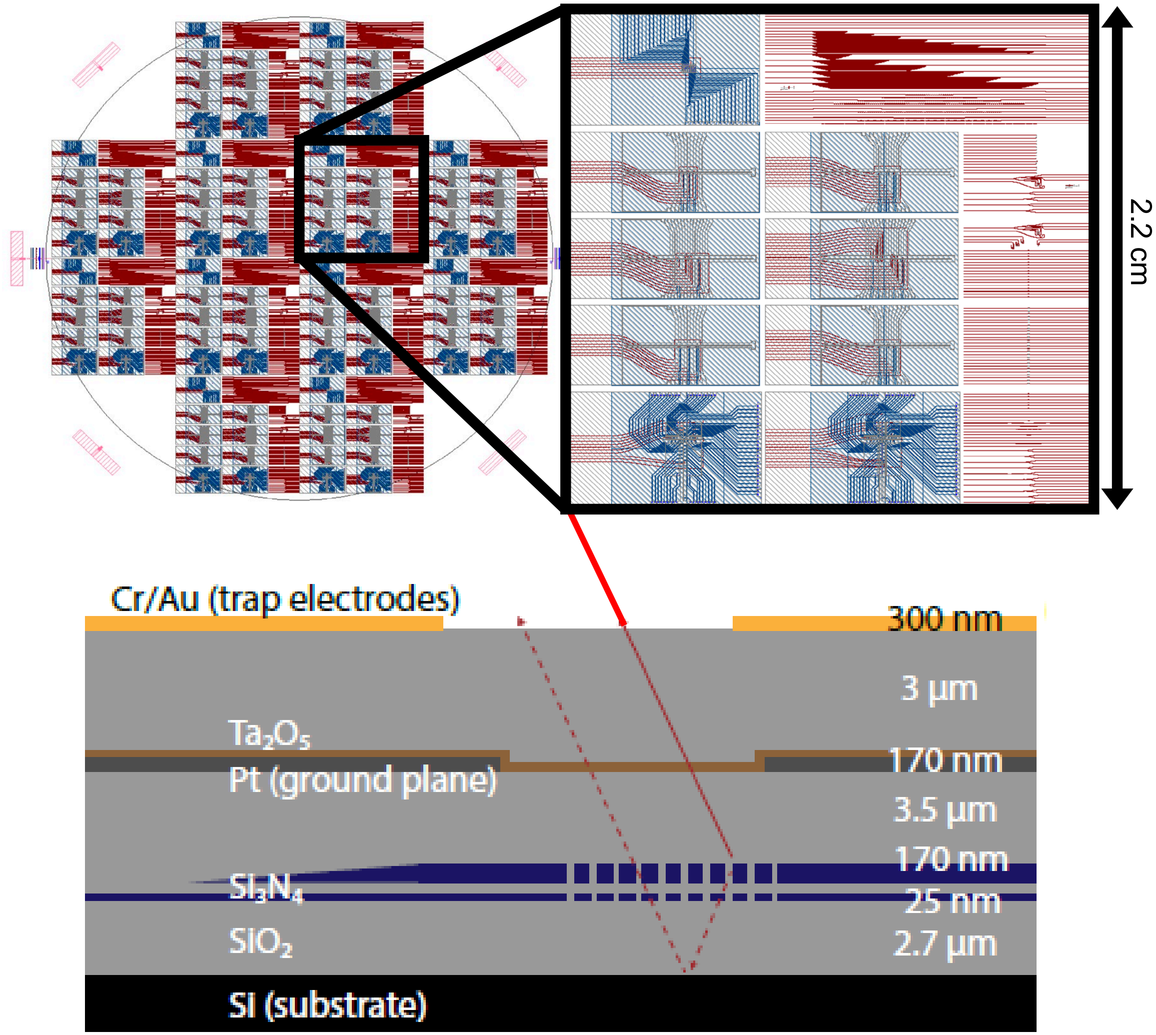
LioniX INTERNATIONAL

Routing



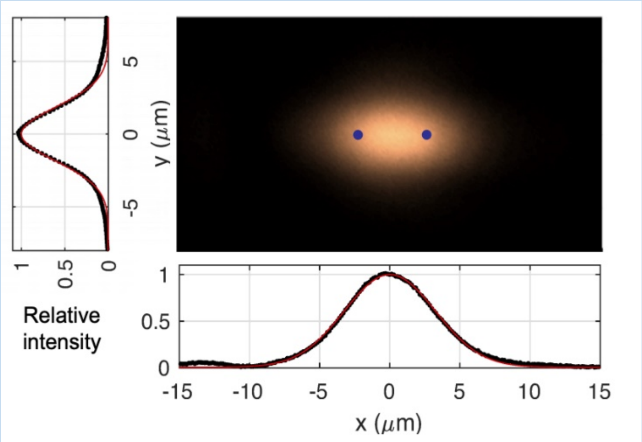
Fiber matching



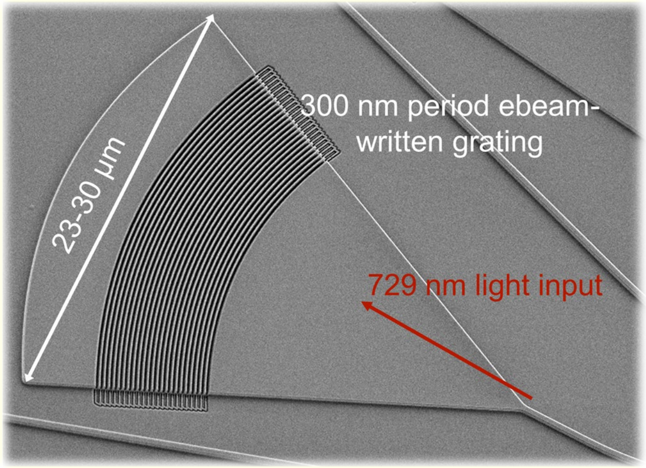


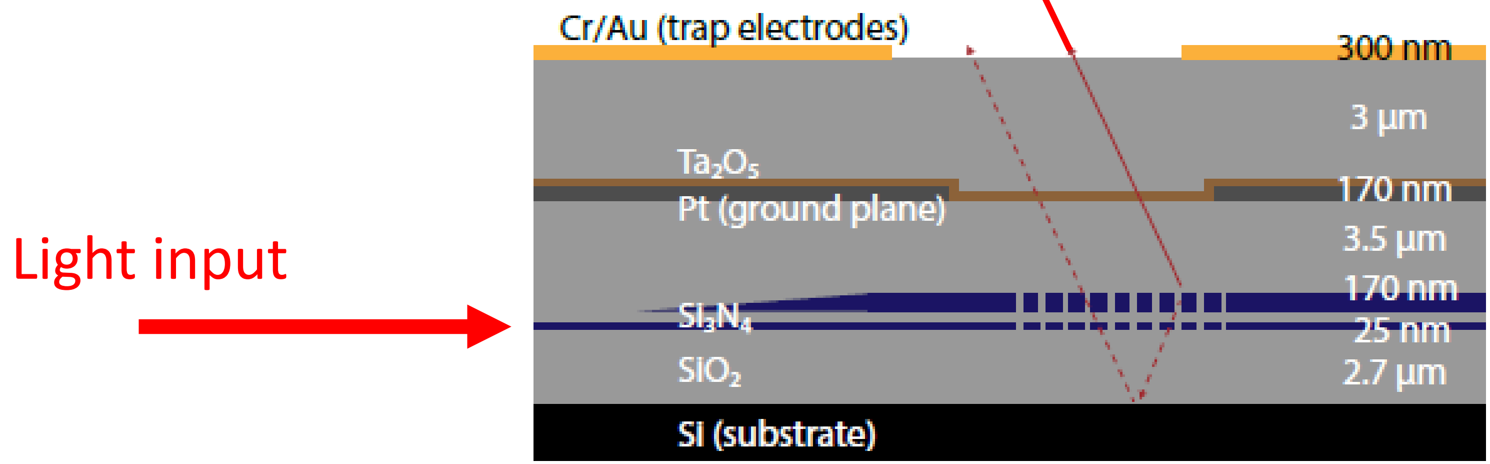
Diffraction to the ion

6.5 µm x 3.7 µm focus (2 ions)



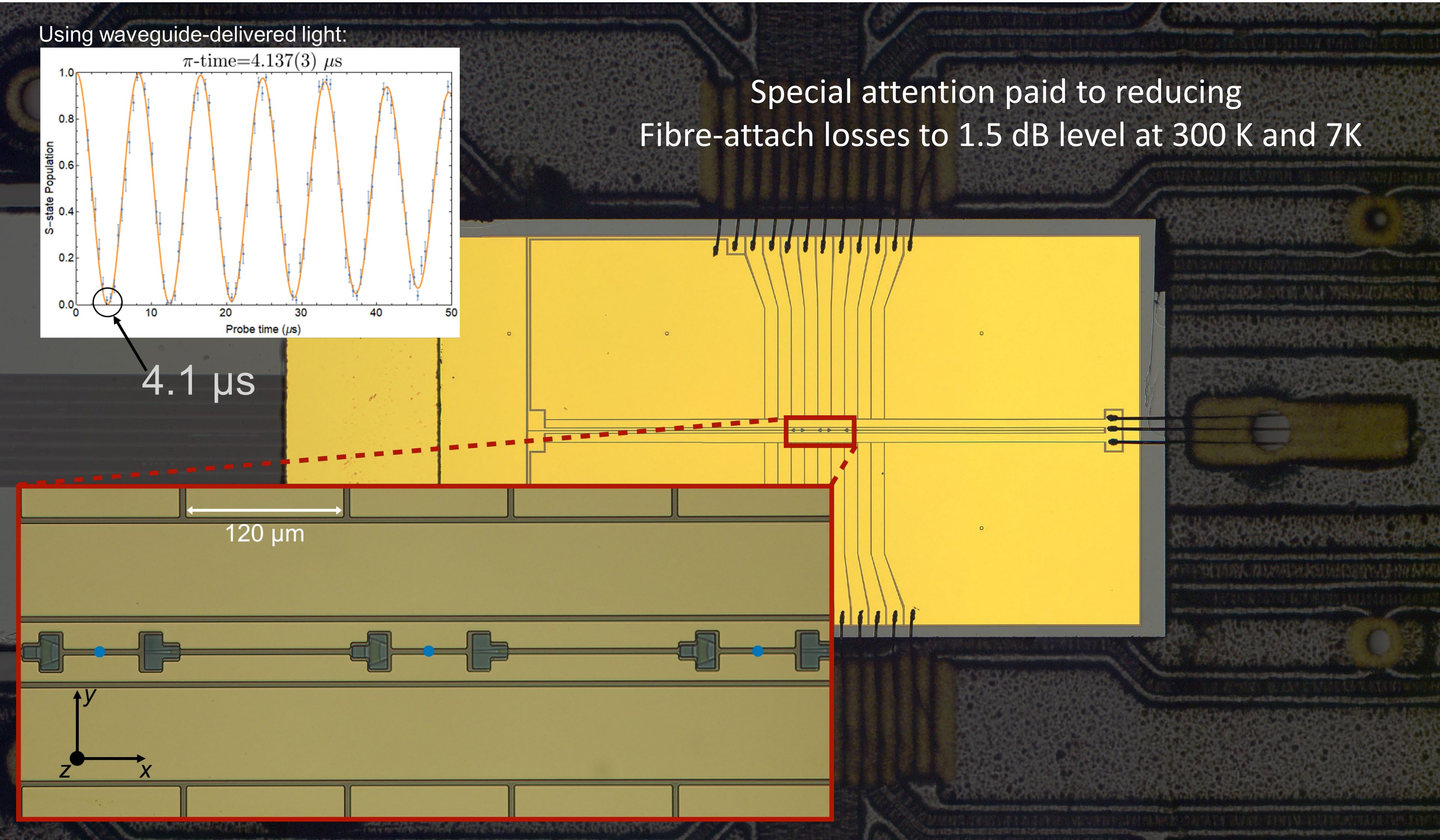
Light to ion
50 micron above surface





Integrated waveguide chips: ETH no. 6

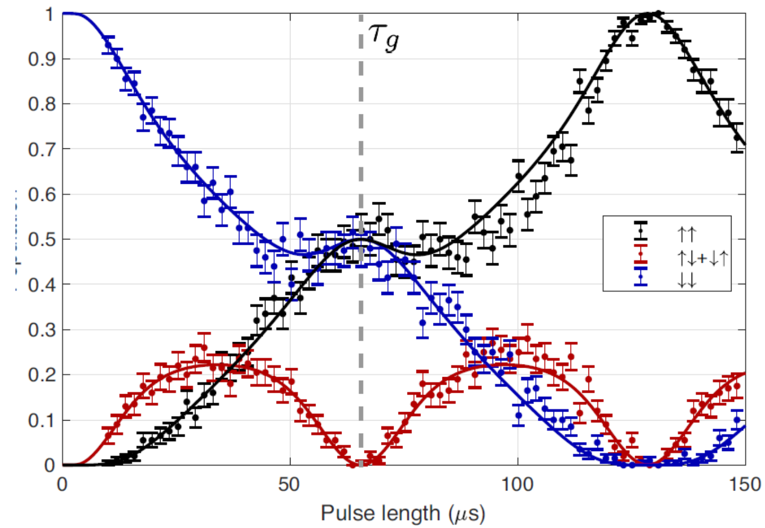
K. Mehta, M. Malinowski, C. Zhang et al. arXiv:2002.03358 (2020)



ETH chip 7: Multi-qubit gates using integrated photonics

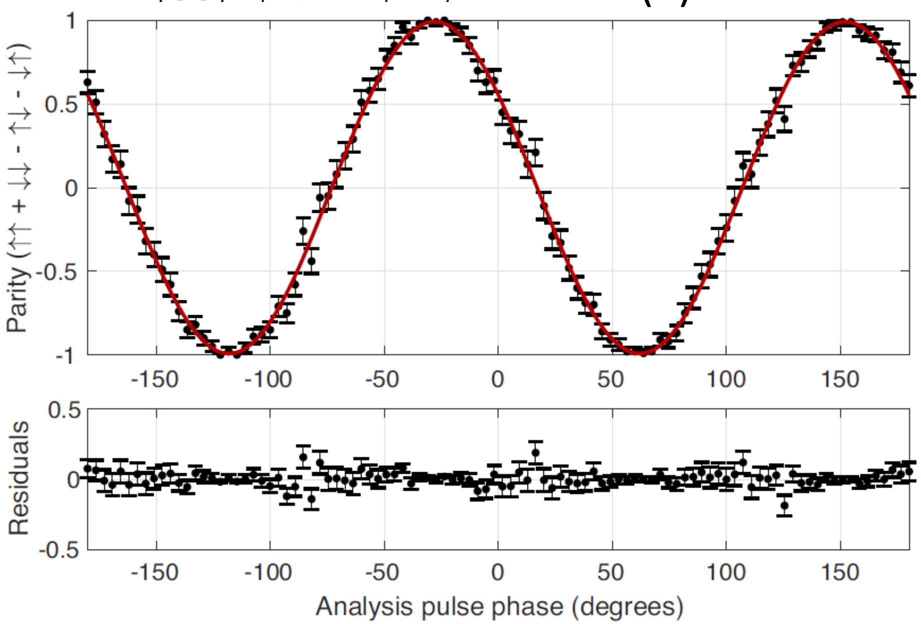
K. Mehta, M. Malinowski, C. Zhang et al. arXiv:200203358 (2020) Nature, in press

Gate time 65 us



1.5 mW emitted from coupler

$|00\rangle + e^{2i\phi}\,|11\rangle$ F = 99.3(2) %

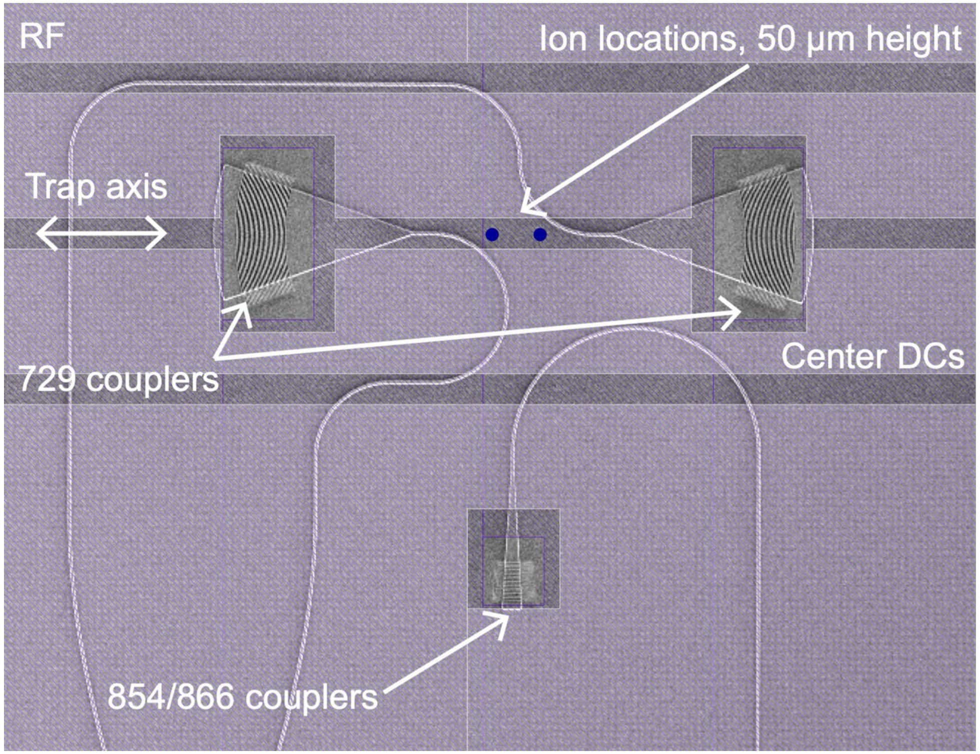


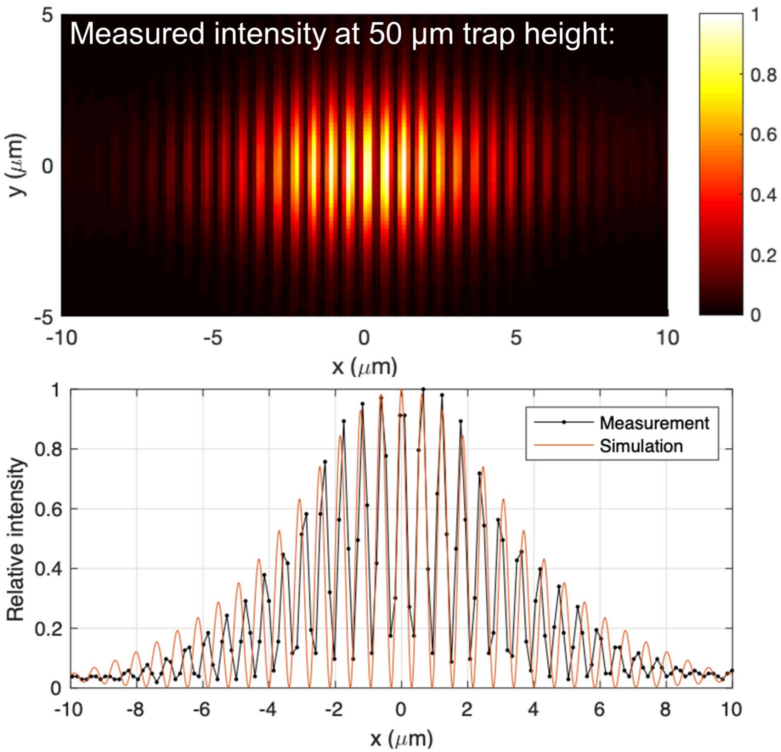
Error source	Infidelity ($\times 10^{-3}$)
Motional mode heating	2(1)
Motional frequency drifts	1
Laser frequency noise	1
Two-ion readout error	0.5
Kerr cross-coupling	0.4
Spectator mode occupancies	0.3
Spontaneous emission	0.03
Total	$\sim 5 \times 10^{-3}$

“Raw” fidelity – mitigation techniques known

Trap-integrated waveguides: standing-wave MS gates

K. Mehta et al. SPIE OPTO (2019)





At anti-nodes we have ***gradients*** but no field, and vice-versa

Travelling wave "standard" gate

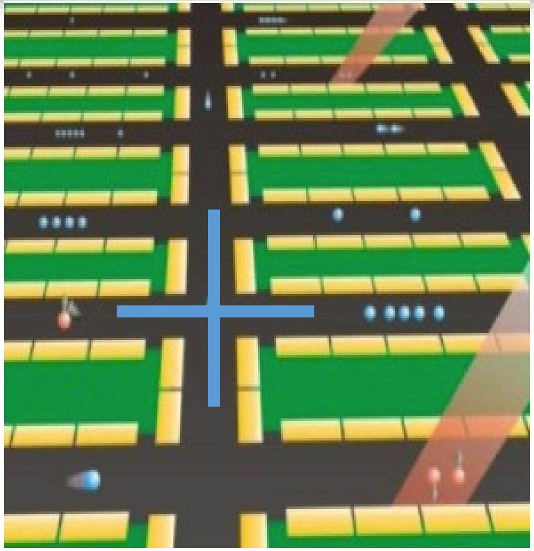
$$E \propto E_0 \sin(kx - \omega t)$$

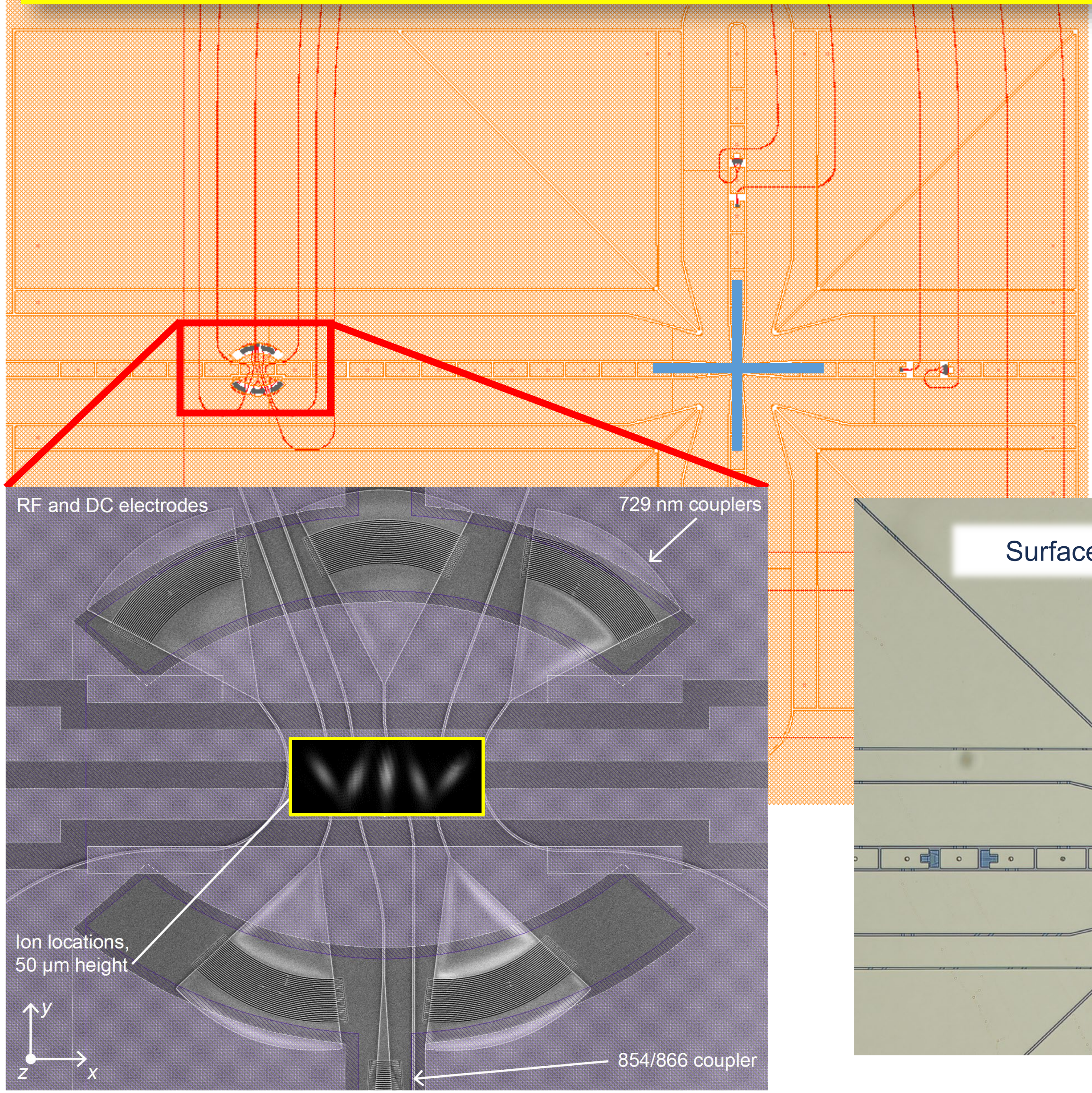
Standing wave – no direct spin drive at node

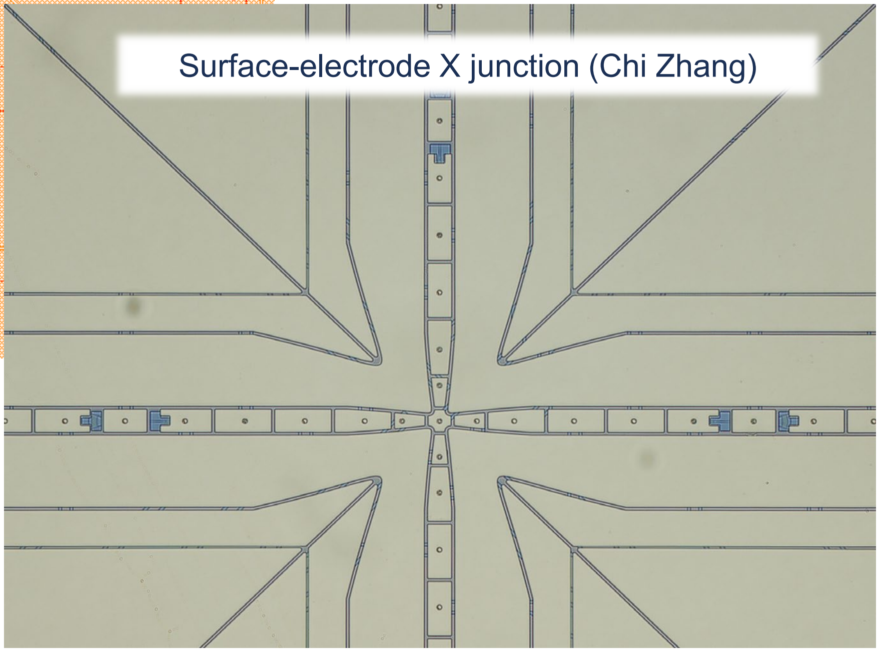
$$E \propto E_0 \sin(kx) \sin(\omega t)$$

Enables MS gate without limitation of off-resonant carrier drive

Trap-integrated waveguides: beyond a single zone





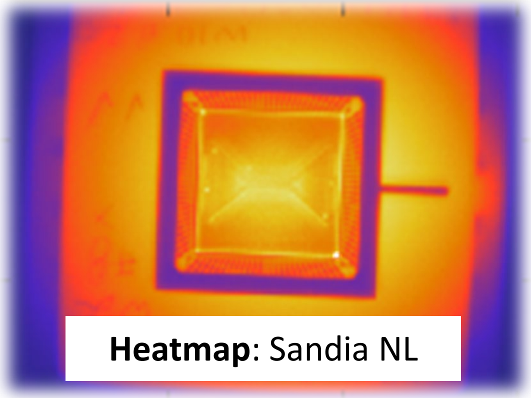


Scaling up – challenges of RF traps

Radio-frequency trap

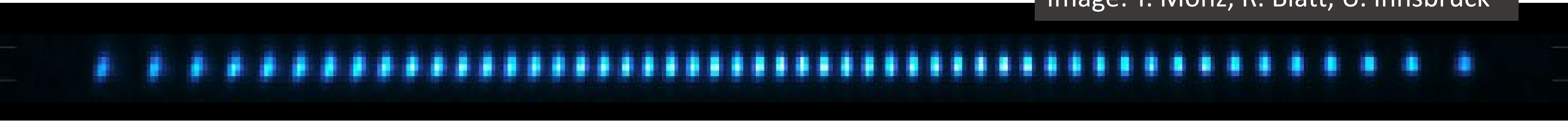
$$V_{\text{static}}(\mathbf{r}) + \Phi_{\text{RF}}(\mathbf{r})$$

- RF null intrinsically 1-D
- Co-alignment of RF and static potentials
- Heating of ion trap chips

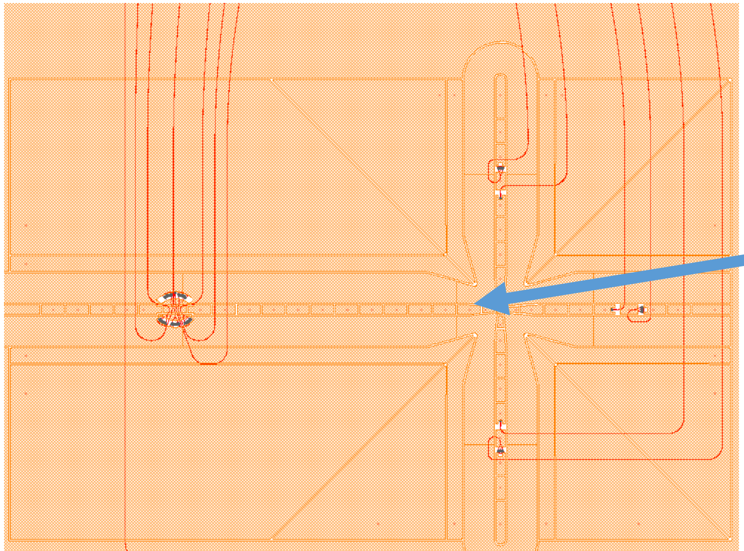


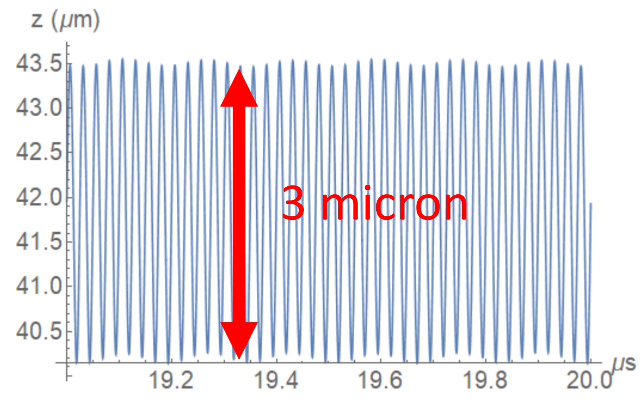
Heatmap: Sandia NL

Image: T. Monz, R. Blatt, U. Innsbruck



Junction trap with waveguides (Chi Zhang)



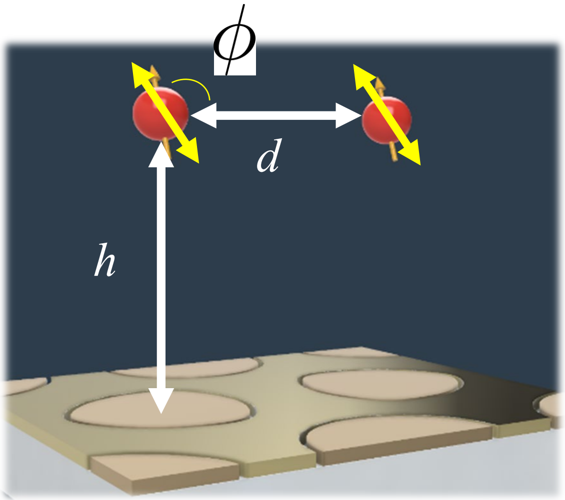


(Out-of-plane direction)

Individual ions in micro-traps

RF traps @ NIST, Freiburg, Sussex

Closely spaced 0-dimensional static + RF potentials $\sum_i V_i(\mathbf{r}_i) + \sum_i \Phi_{\mathrm{RF},i}(\mathbf{r}_i)$



Normal modes split similar to dipole-dipole coupling

$$\Omega_{\mathrm{ex},z}(1 - 3\cos^2(\phi))\left(a_i {a_j}^\dagger + a_j {a_i}^\dagger\right)$$

$$\Omega_{\mathrm{ex,z}} = \frac{e^2}{4\pi\epsilon_0 M \omega_z d^3} \propto \frac{z_0^2}{d^3}$$

Zero point motion

- Hard to get small scales – anomalous heating limits height
- Limited mode splitting limits spectral isolation for 2-qubit gates

2-qubit gate: Wilson et al. Nature 512, 57–60(2014)

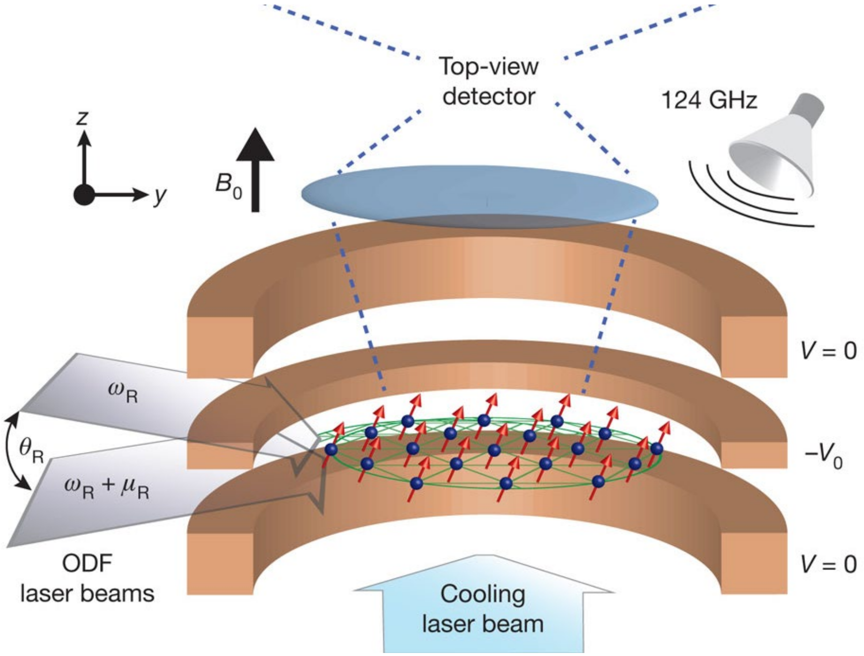
Penning traps

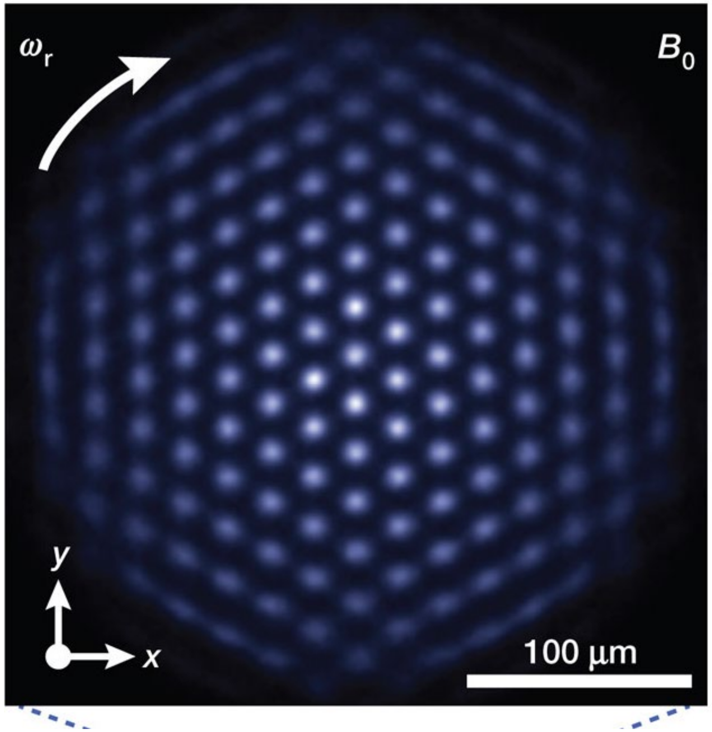
Multi-ion crystals + quantum control: NIST, Imperial, Sydney

$$V(z^2 - (x^2 + y^2)/2) + \{\mathbf{B}\hat{z}\}$$

Single potential well – (rotating) ion crystals of > 100 ions

J. Bollinger et al, NIST

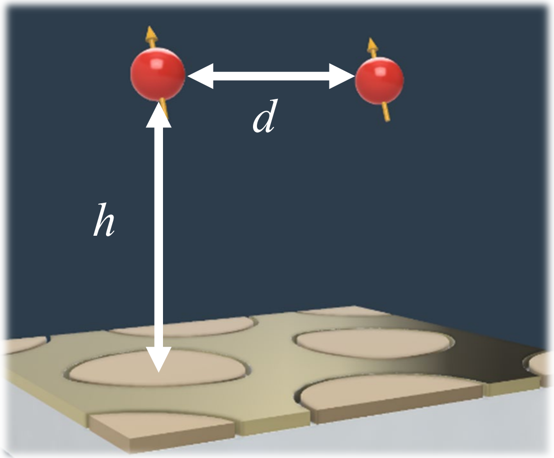




Penning trap arrays

S. Jain, J. Alonso, M. Grau et al. PRX, 10, 3, 031027 (2020)

$$\sum V_i(\mathbf{r}_i) + \Phi_{\mathrm{RF},i}(\mathbf{r}_i) \quad \Rightarrow \quad \sum_i V_i(\mathbf{r}_i) + \{\mathbf{B}\}$$



Static potentials stronger than RF pseudopotentials

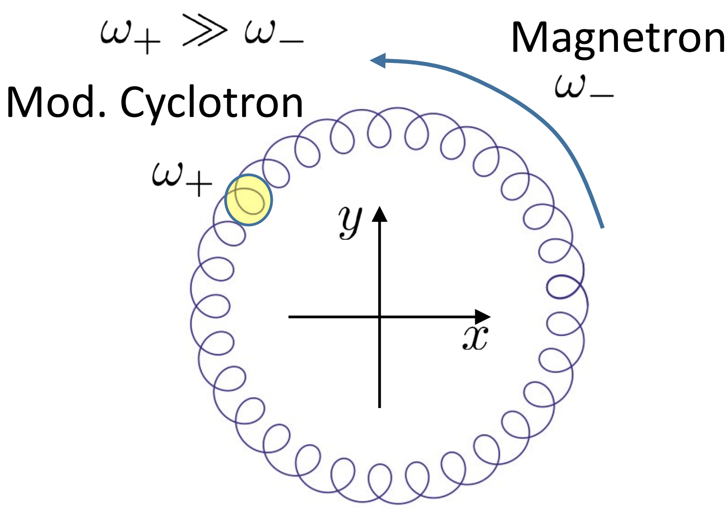
Lower voltage for same trap spacing

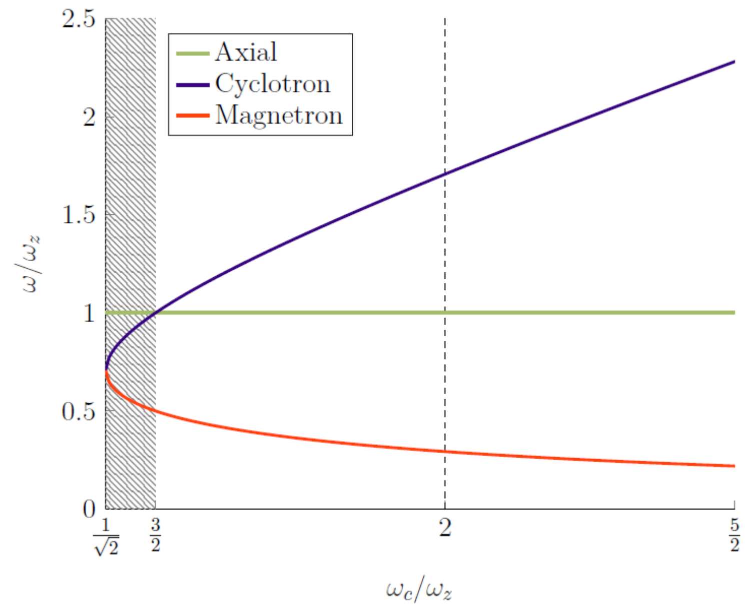
$$||\,\Psi^{(2)}_{\mathrm{RF}}\,|| = \underbrace{\frac{\sqrt{3}}{8}|\,q_z\,|}_{\sim 1/16} \cdot ||\,\Pi^{(2)}\,||$$

P.P. curvature — Static curvature

- Traps use only static fields
- Reduced sensitivity to stray fields (B field is homogeneous)
- Power dissipation minimal (during cooling)

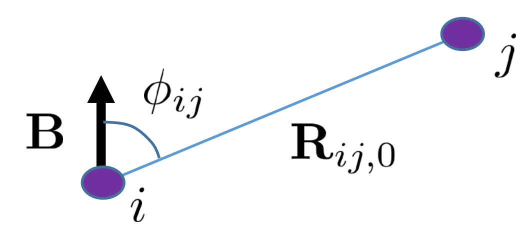
Couplings + zero-point motion





Neighboring similar traps: Coulomb couplings (perturbative)

$$(-1)^{\nu}\Omega_{\mathrm{ex},\nu}(1-3\cos^2(\phi_{ij}))\left(a_i a_j{}^{\dagger}+a_j a_i{}^{\dagger}\right)$$



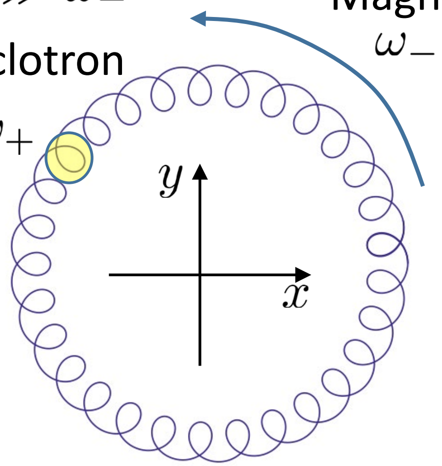
Dipoles **for all modes** act as if they point along the B field

$$\Omega_{\mathrm{ex,z}}=\frac{e^2}{4\pi\epsilon_0 M\omega_z d^3}\qquad\qquad \Omega_{\mathrm{ex},\pm}=\frac{e^2}{4\pi\epsilon_0 M(\omega_+-\omega_-)d^3}$$

Enhanced zero-point motion: consequences

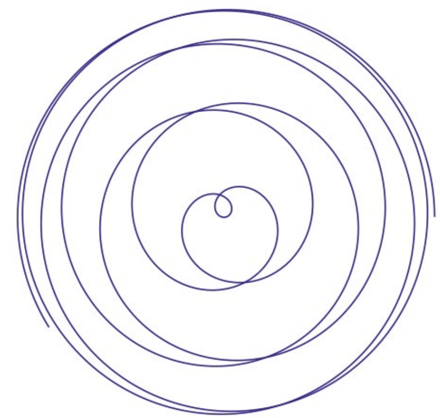
Zero-point motion relates to frequency at which potential energy is modulated

$\omega_+ \gg \omega_-$



$$z_0 = \sqrt{\frac{\hbar}{2m(\omega_+ - \omega_-)}}$$

$\omega_+ - \omega_- \ll \omega_\pm$



- couplings enhanced $\Omega_{\text{ex}} \propto z_0^2$
- Laser or B-field motion coupling enhanced $\Omega_{\text{g}} \propto k z_0 \Omega$ or $\Omega \propto z_0 \partial_z B$
- Heating "enhanced"

$$\dot{n}_+ = \frac{e^2}{4m(\omega_+ - \omega_-)} S_E(\omega_+)$$

Enhancement → (denominator $4m(\omega_+ - \omega_-)$)

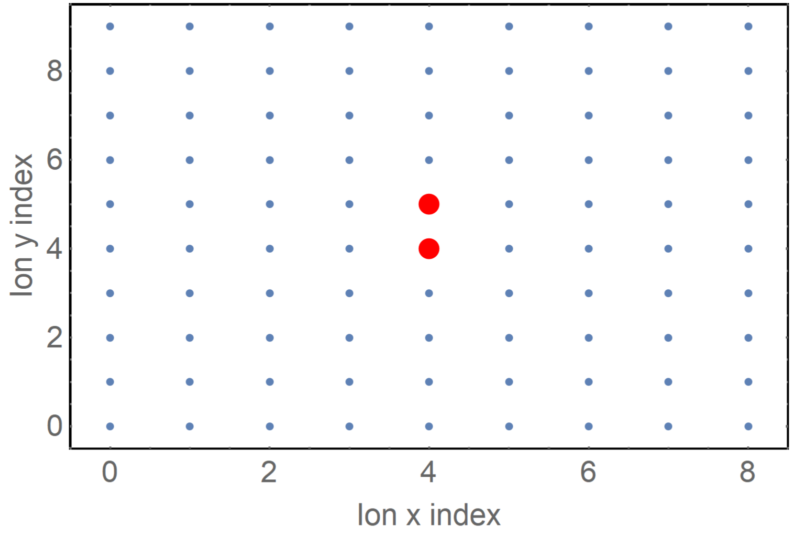
Noise sampling frequency → (ω_+)

Quantum computation on a fixed lattice

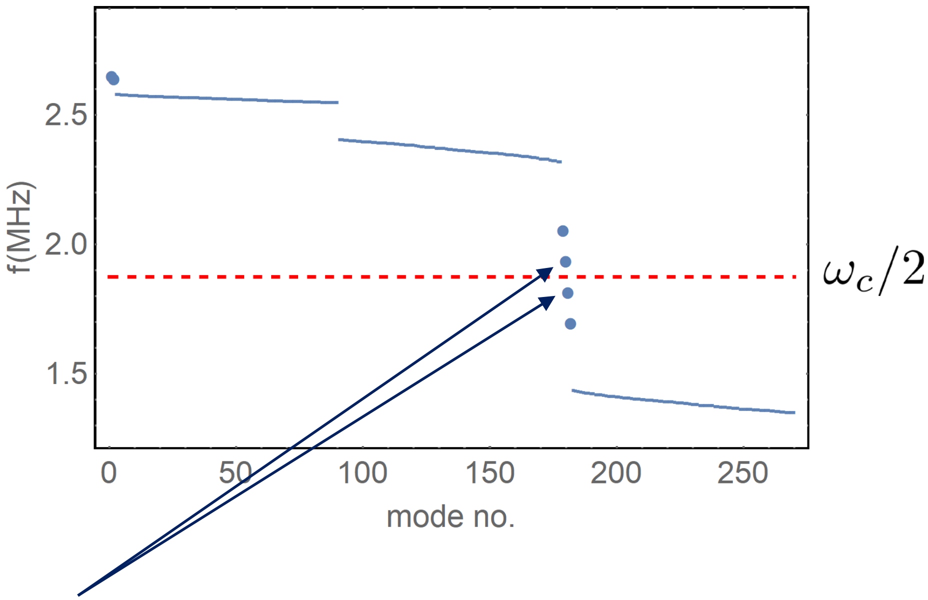
S. Jain, J. Alonso, M. Grau et al. PRX, 10, 3, 031027 (2020)

Selective tuning of ion frequencies to "large" zero-point motion

Example: 90 beryllium ions, B-field in-plane,
30 micron ion spacing



Mode spectrum



"Stretch" modes: $\delta/(2\pi) \simeq \pm 60\ \mathrm{kHz}, z_0 \simeq 96\ \mathrm{nm}$

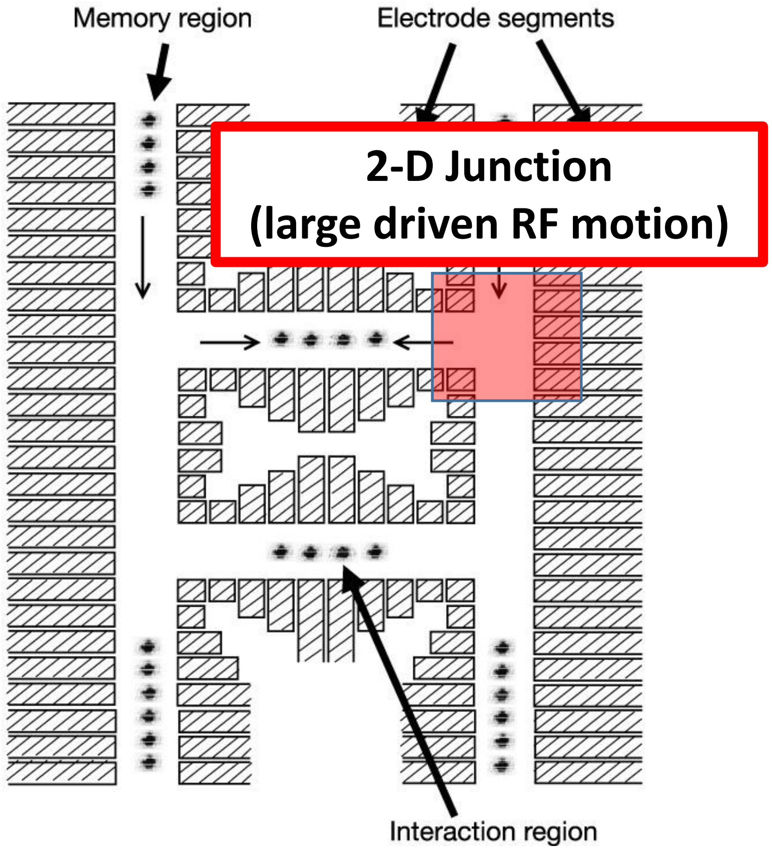
Well isolated + large zero-point motion: good for 2-qubit gate!

Laser "gate" drive at $\mu \simeq \omega_c/2$

"Theoretical "F > 0.9998 in 16 microseconds, $\Omega_c = 2\pi \times 300\ \mathrm{kHz}, \Delta\phi = \dfrac{\pi}{40}$

Quantum computation on a movable lattice

Kielpinski et al. Nature (2002)

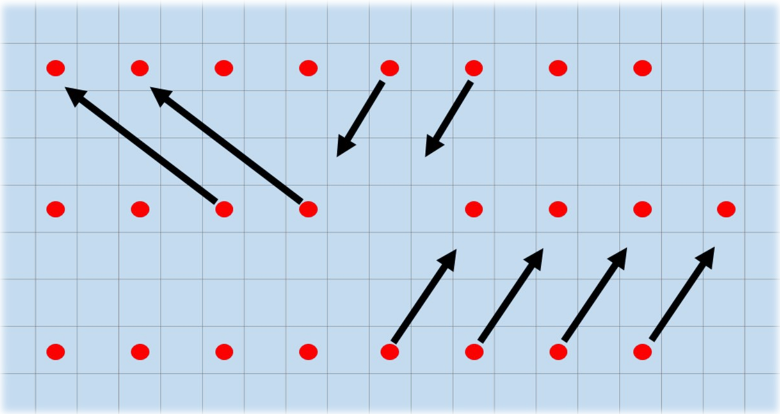


Penning: 2-D transport at any position

<u>Homogeneous</u> magnetic field

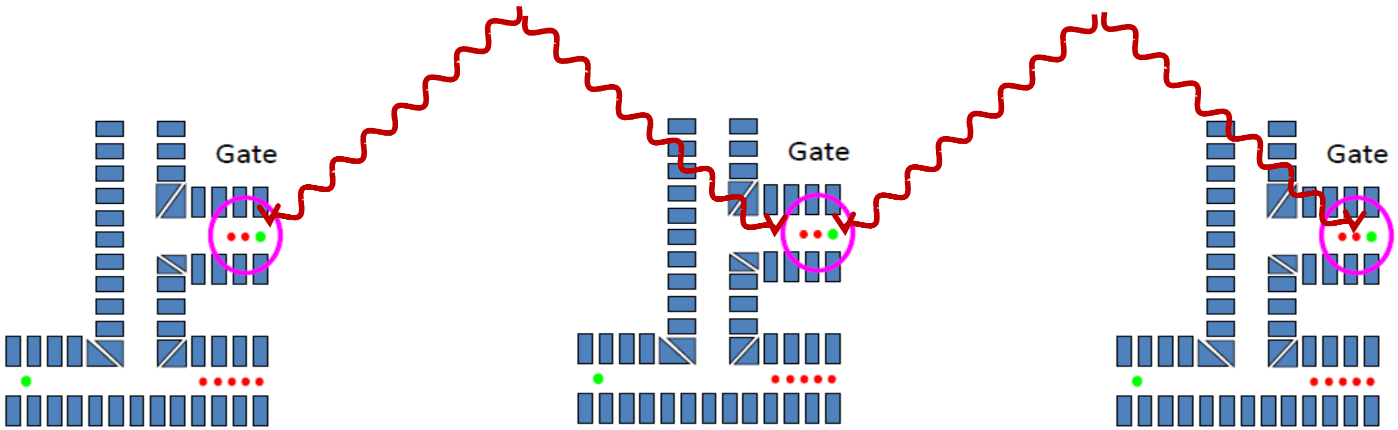
- 3-dimensional transport accessible
- stray fields primarily cause frequency shifts

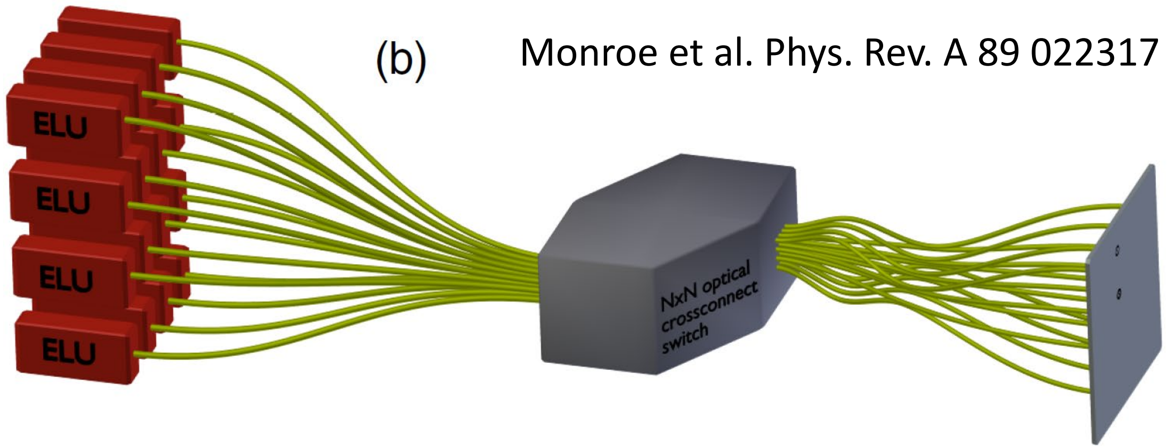
Previous work: Hellwig et al. NJP 12 065019 (2010)
Crick et al. RSI 81, 01311 (2010)



Optical connections

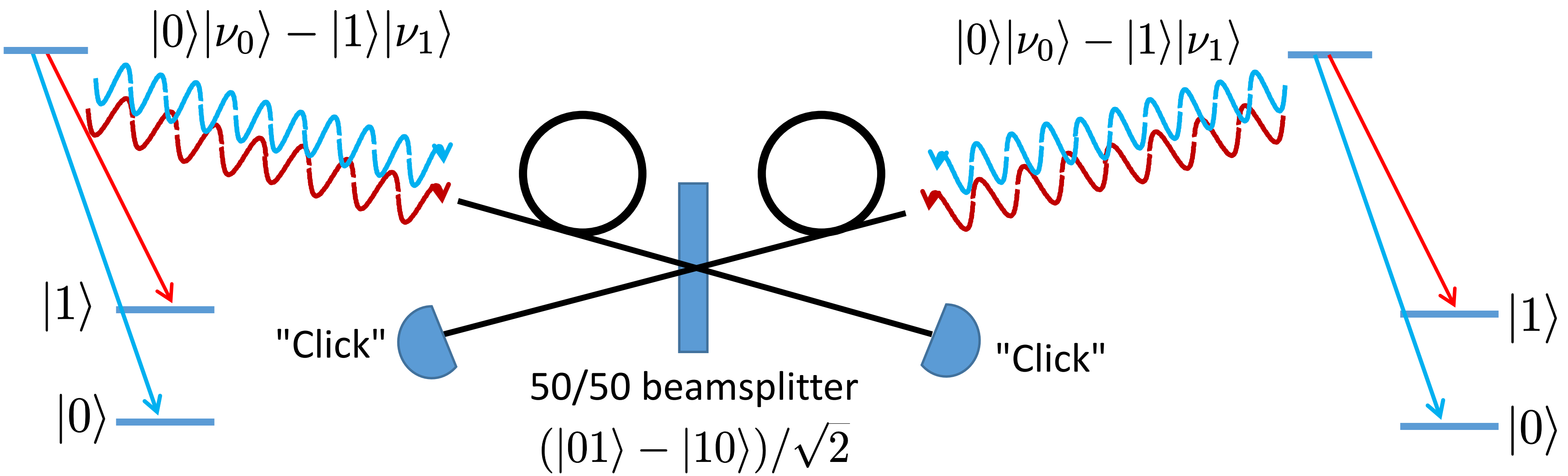
Multiple small processors linked by probabilistic entanglement generation and teleportation





Monroe et al. Phys. Rev. A 89 022317 (2014)

Probabilistic remote entanglement generation

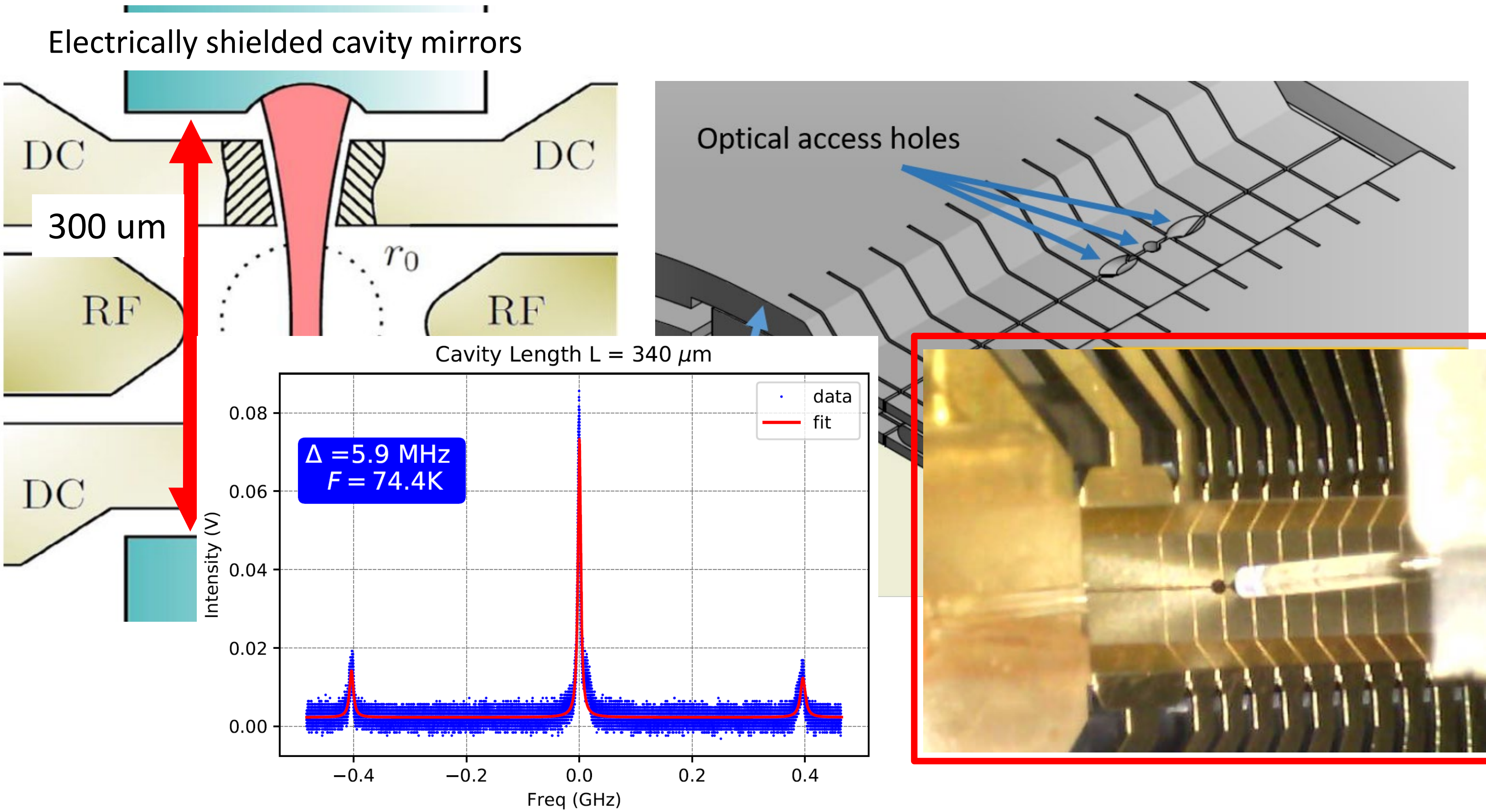


- Entangled ions separated by **1m** (Moehring et al. Nature 449, 68 (2008))
- More recent: entanglement rate up to 180 Hz ((2020))

Ultimately requires optical cavities for higher rates.

Efficient single ion – single photon interfaces

Single-atom -> single photon: optical Fabry-Perot cavity
Must shield charge of ion from charges on mirror surfaces

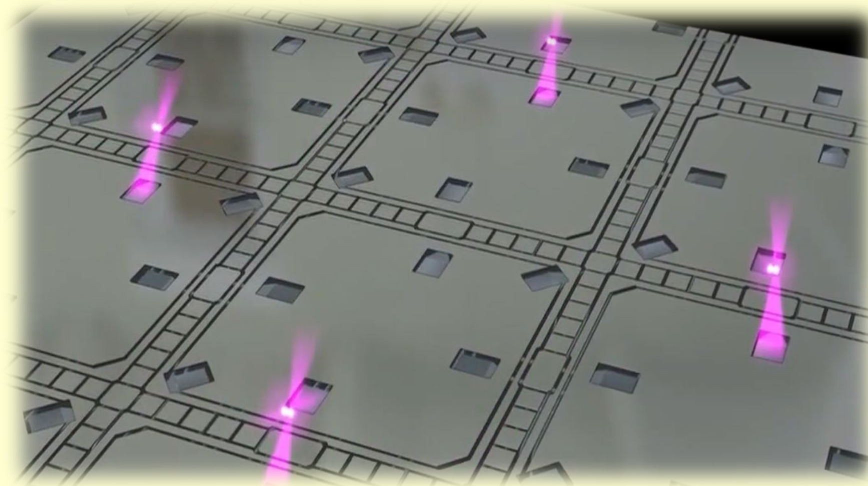


Summary of TIQI results

Integrated optics for quantum control

- High-fidelity multi-qubit gates

K. Mehta et al. arXiv:200203358 (2020)

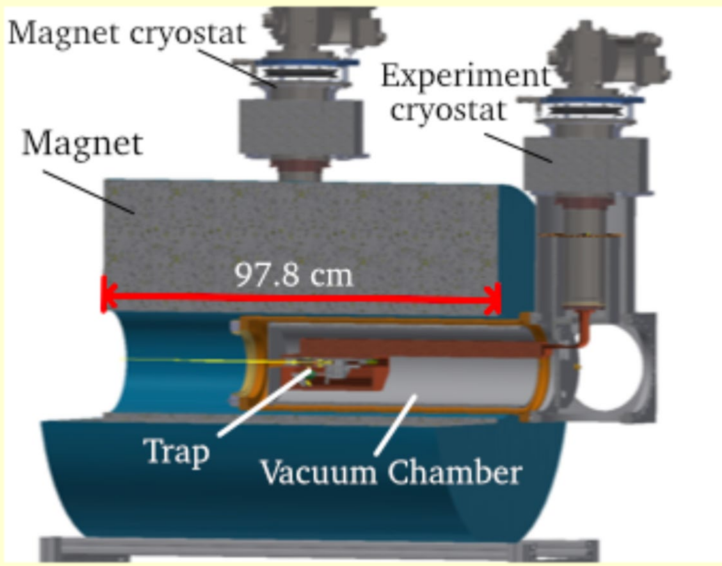


Micro-Penning traps for scaling to 2D

- Quantum simulations
- Quantum computation

S. Jain et al. PRX, 10, 3, 031027 (2020)
(Multi-ion invariance, theory of normal modes)

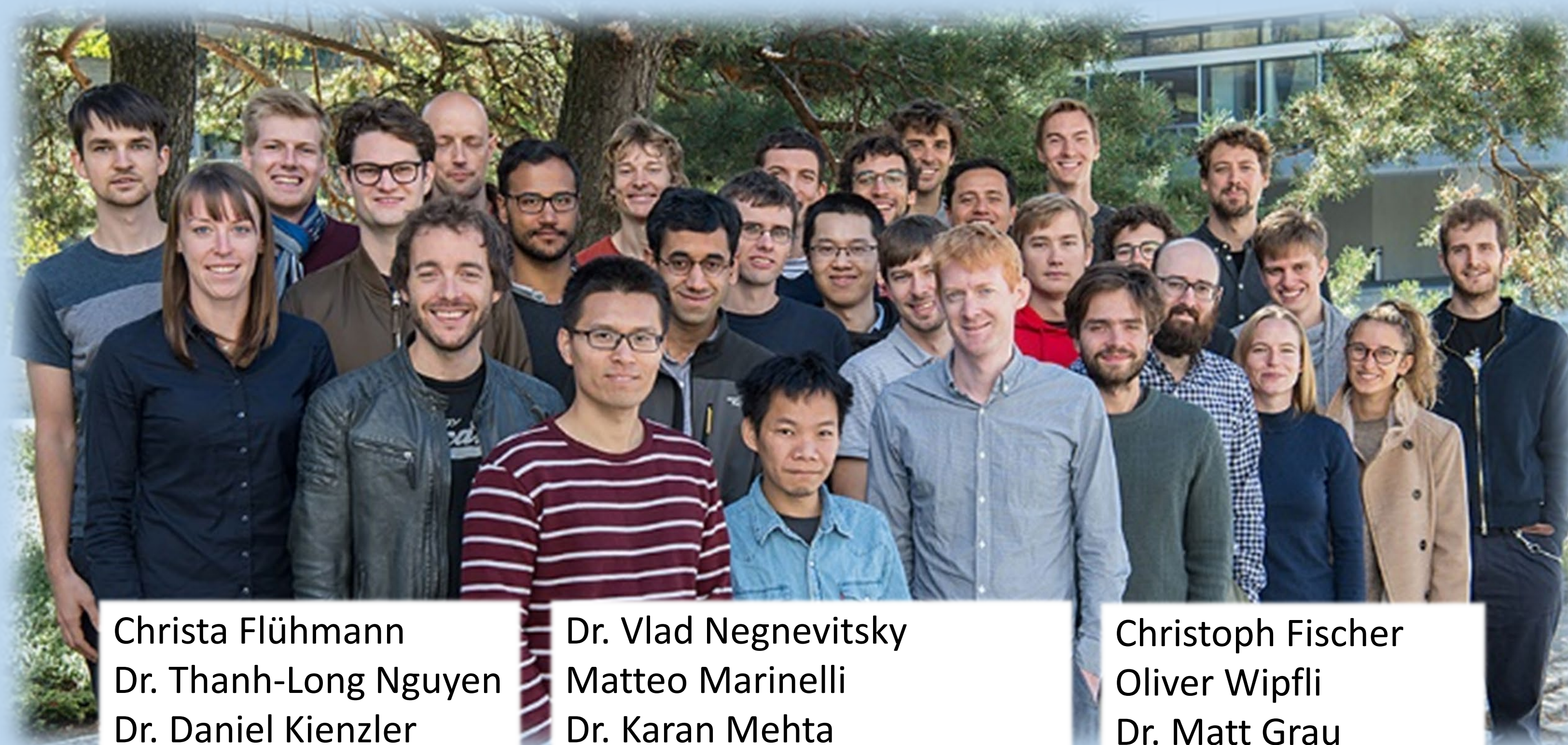
European Research Council
Established by the European Commission



Trapped Ion Quantum Information Group

ETH Zürich

www.tiqi.ethz.ch



Christa Flühmann
Dr. Thanh-Long Nguyen
Dr. Daniel Kienzler
Robin Oswald
Roland Matt
Chiara Decaroli
Simon Ragg
Dr. Thomas Lutz
Dr. Celeste Carruth

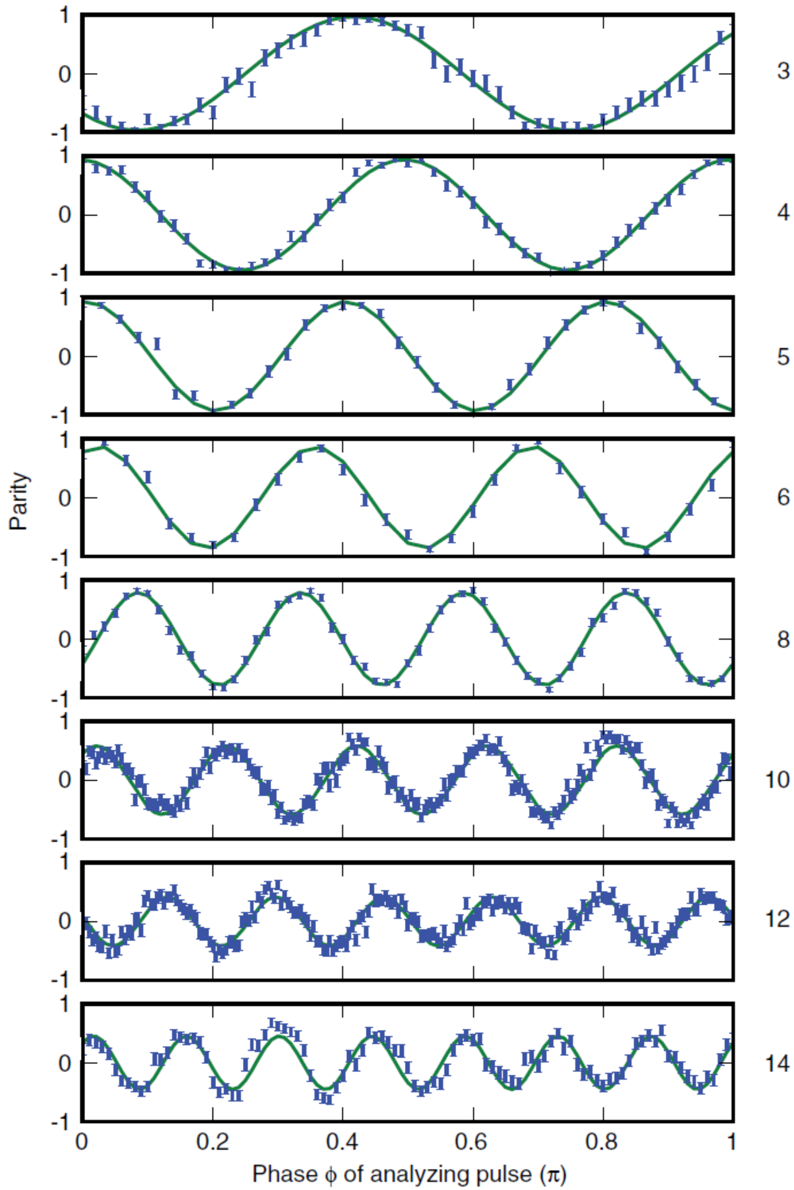
Dr. Vlad Negnevitsky
Matteo Marinelli
Dr. Karan Mehta
Tanja Behrle
Francesco Lancelotti
Brennan McDonald deNeeve
Maciej Malinowski
Chi Zhang

Christoph Fischer
Oliver Wipfli
Dr. Matt Grau
Shreyans Jain
Nick Schwegler
Tobias Saegasser
Dr. Chris Axline
Martin Stadler

GHZ States of up to 14 ions

Monz et al., PRL 106, 130506 (2011), Innsbruck – Blatt group

$$\left(|11...1\rangle + |00...0\rangle\right)/\sqrt{2}$$

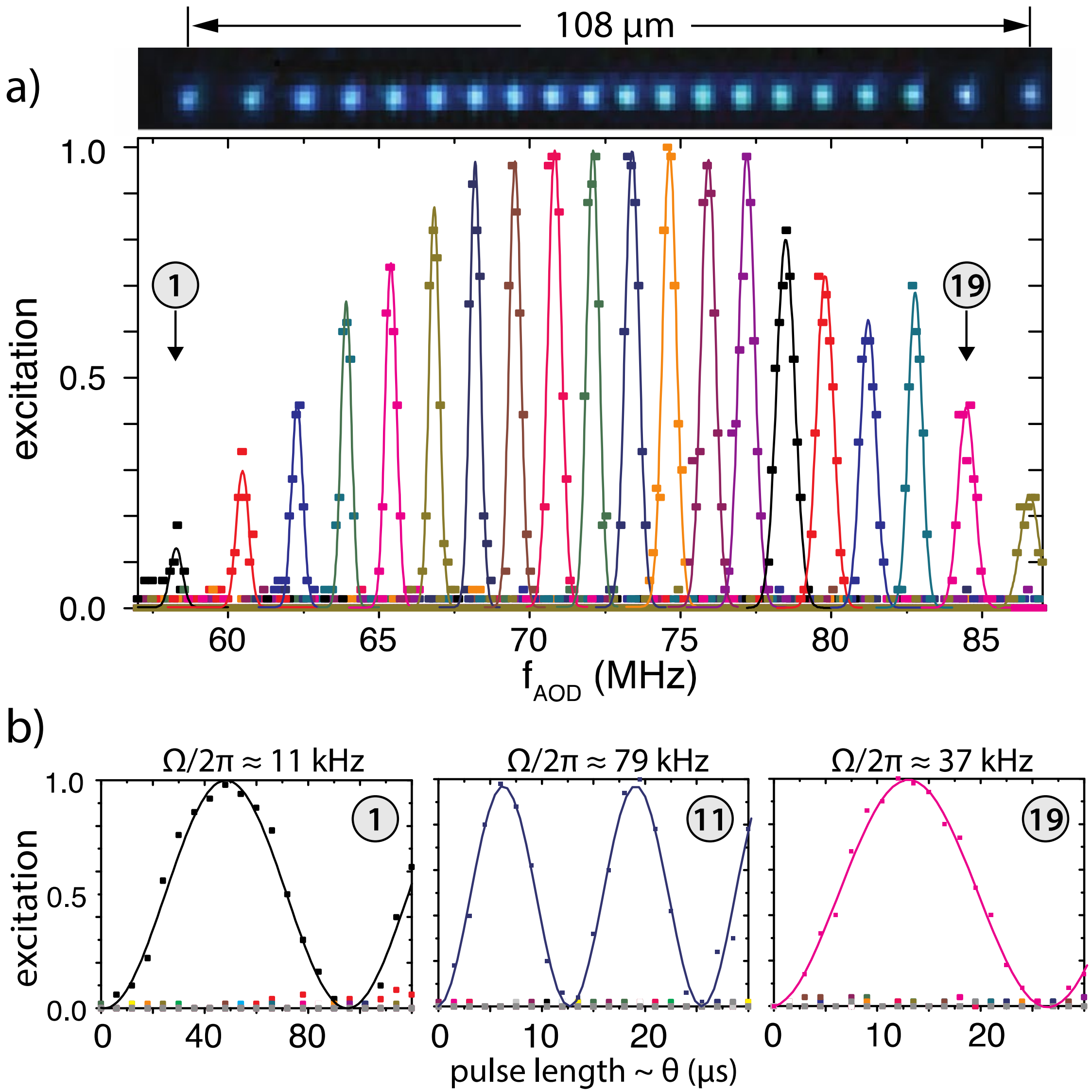


High contrast – 3 ions

Reduced contrast – 14 ions

Individual rotations on a long ion string

Data: C. Hempel, C. Roos, R. Blatt (Innsbruck)



Global Ramsey,
Individually addressed Stark

Engineered spin-spin interactions

Go to limit of large motional detuning
(very little entanglement between spin and motion)

$$\Omega \ll \delta$$

$$\Phi_{10} = \Phi_{01} \simeq \frac{\Omega^2}{\delta} t$$

$$\frac{1}{2}\left(|00\rangle + |10\rangle + |01\rangle + |11\rangle\right)$$

$$\hat{H}_{\text{eff}} = J \hat{\sigma}_{z,1} \hat{\sigma}_{z,2}$$

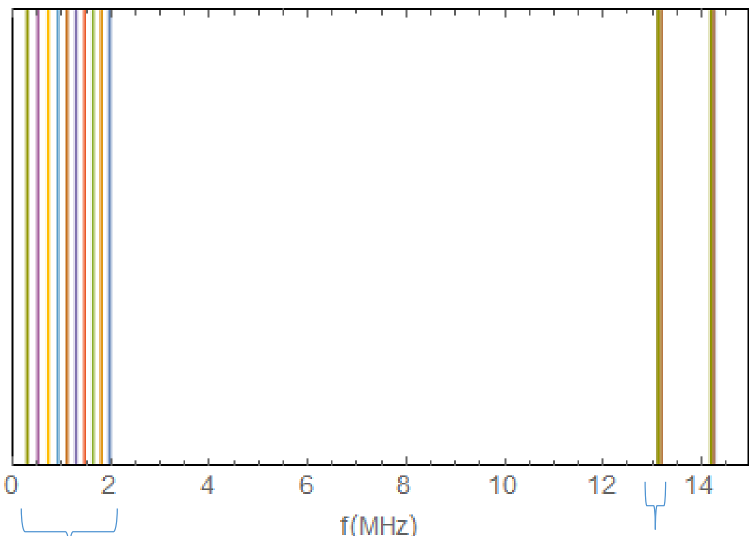
$$\frac{1}{2}\left(|00\rangle + i\,|10\rangle + i\,|01\rangle + |11\rangle\right)$$

Allows creation of many-body Hamiltonians
(Friedenauer et al. Nat. Phys 4, 757-761 (2008)
Kim et al. Nature 465, 7298 (2010))

Linear chains + multiple oscillator modes

Mode frequencies: Be ions $f_x = 13.2 \text{ MHz}, f_y = 14.2 \text{ MHz}$

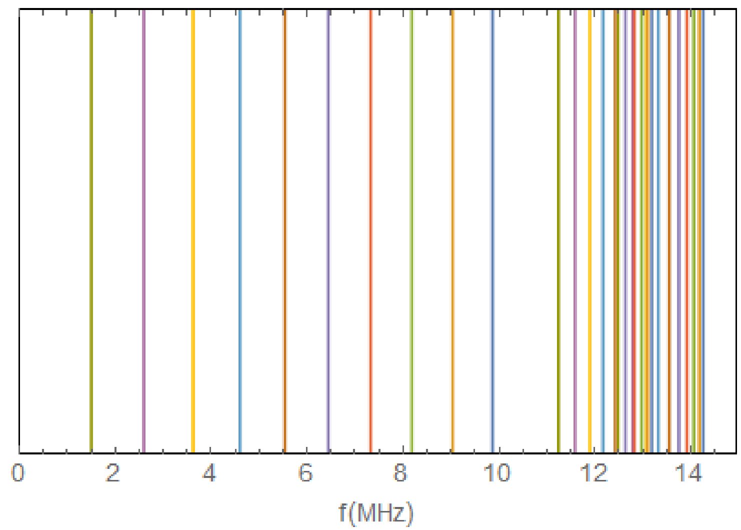
$f_z = 300 \text{ kHz}$



$\sim N_{\text{ions}} f_z$

$\sim f_{\text{exchange}}$

$f_z = 1.5 \text{ MHz}$



$$f_{\text{exchange}} = \frac{1}{2\pi} \frac{e^2}{2\pi\epsilon_0 \omega_\alpha m_{\text{ion}} d^3}$$

$$\hat{H}_{\text{ex}} = h f_{\text{exchange}} \left(\hat{a}^\dagger \hat{b} + \hat{a} \hat{b}^\dagger \right)$$

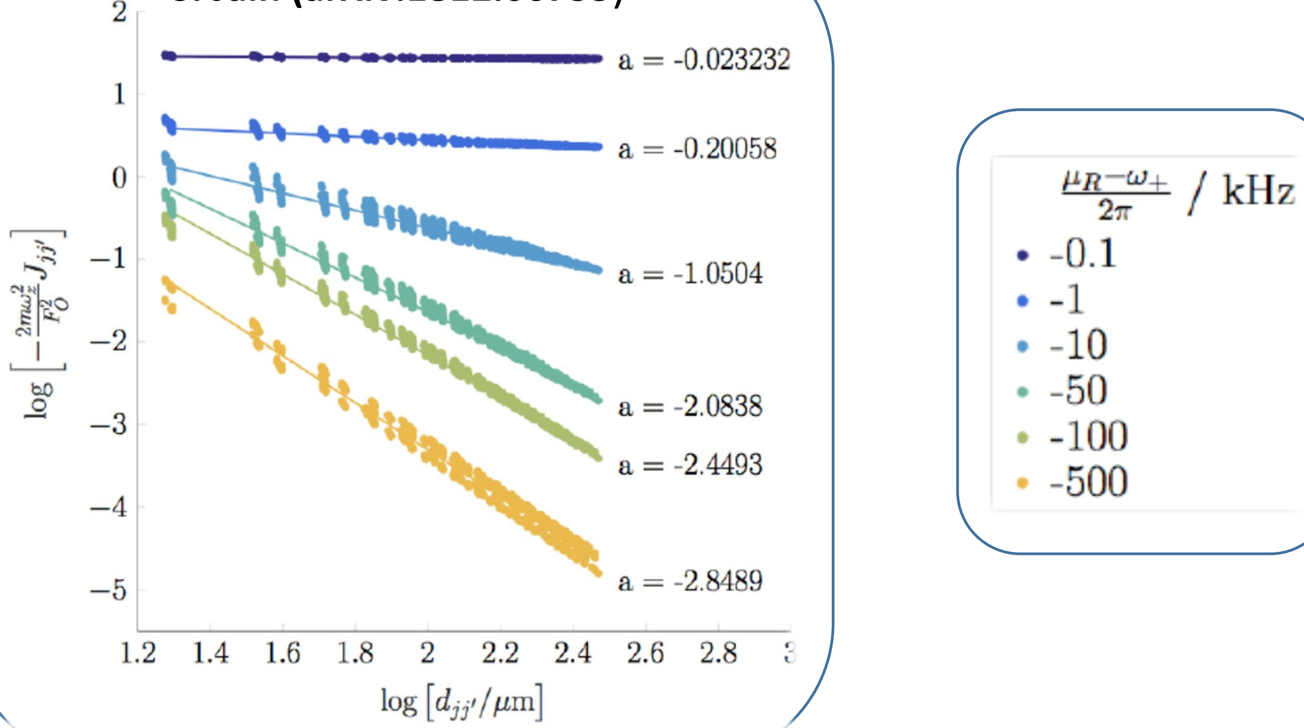
Distance between neighboring ions

Tuneable range spin-spin interactions

$$H_{\mathrm{SPIN}} = \sum_{jj'} J_{jj'}(t)\sigma_j^z \sigma_{j'}^z$$

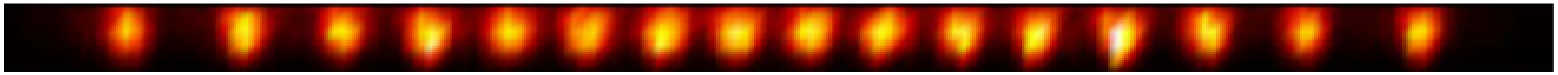
$$J_{jj'}^0 = \frac{E_O^2}{2\hbar} \sum_{\lambda} \frac{\omega_\lambda}{\mu_R^2 - \omega_\lambda^2} \mathrm{Re}\left(\eta_{\lambda j}^* \eta_{\lambda j'}\right)$$

S. Jain (arXiv:1812.06755)

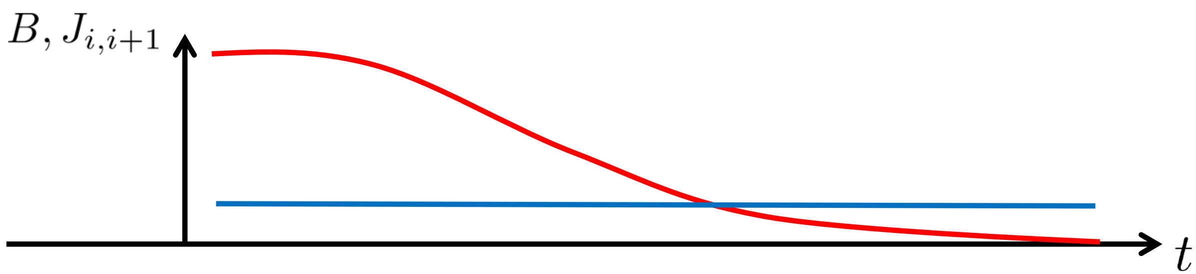


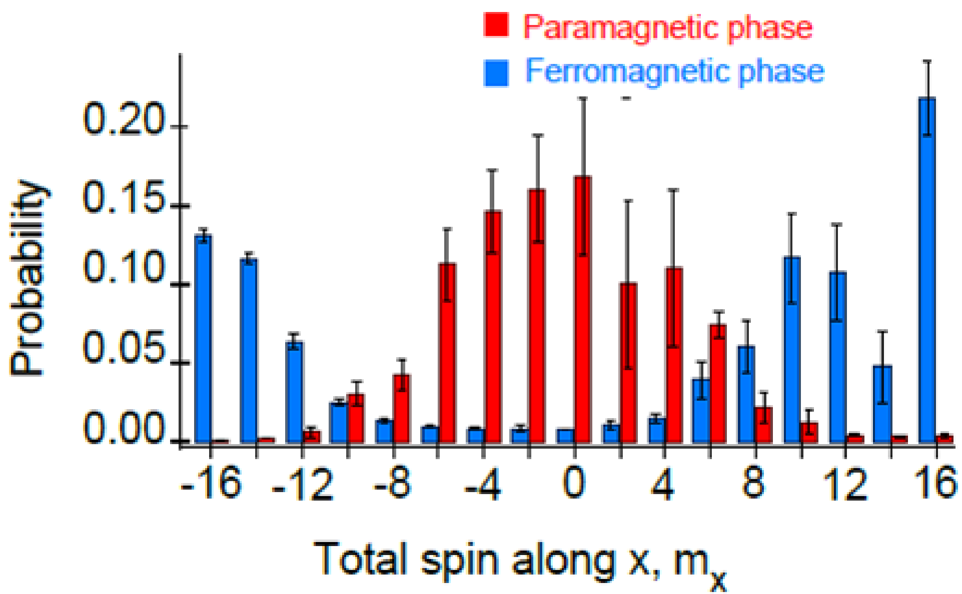
Quantum simulations in long ion strings

(up to 53 ions Zhang et al. Nature 2017)

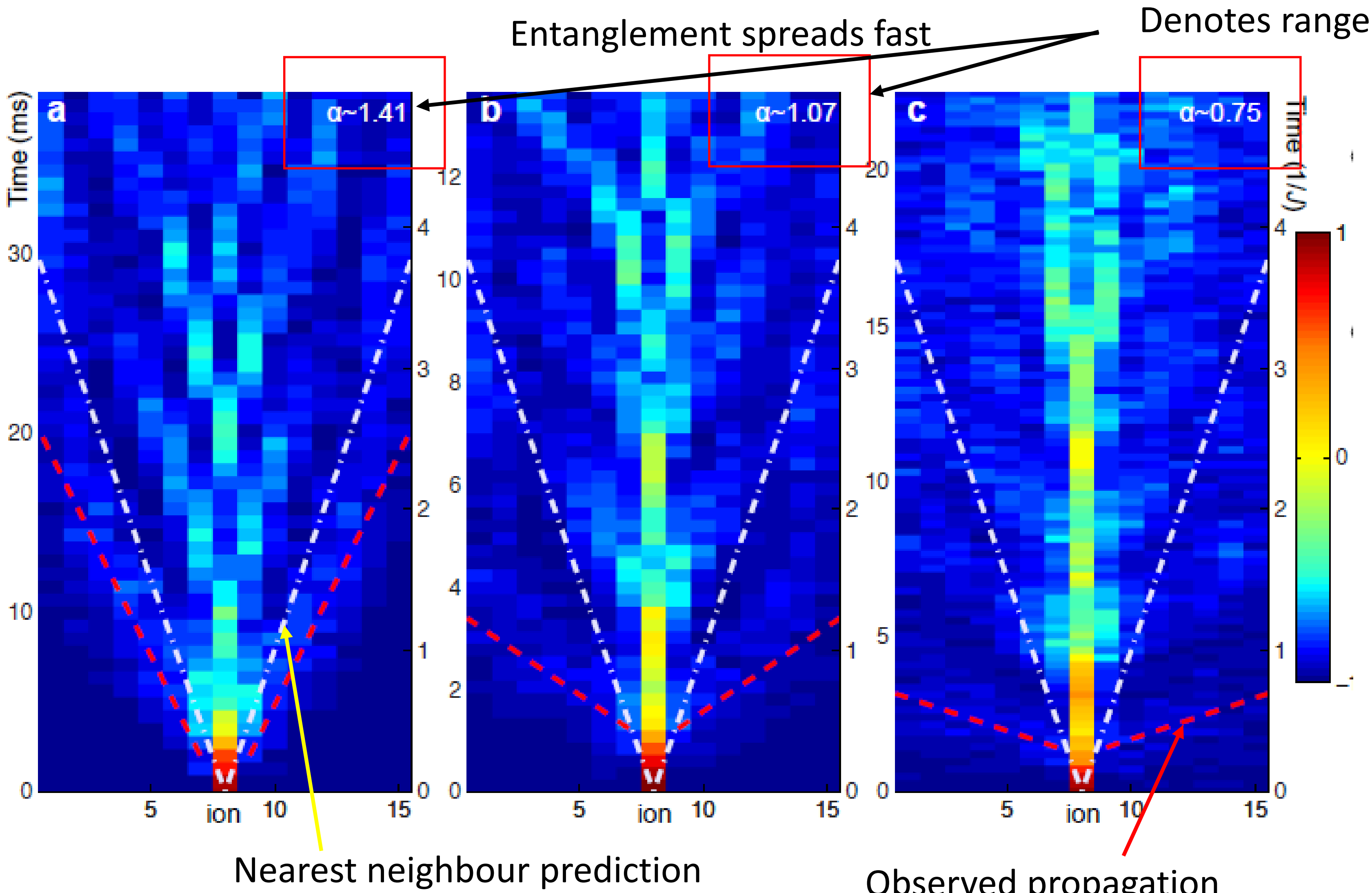


$$\hat{H} = \sum_{j<i} J_{ij}\sigma_x^i\sigma_x^j - B\sum_i \sigma_y^i$$





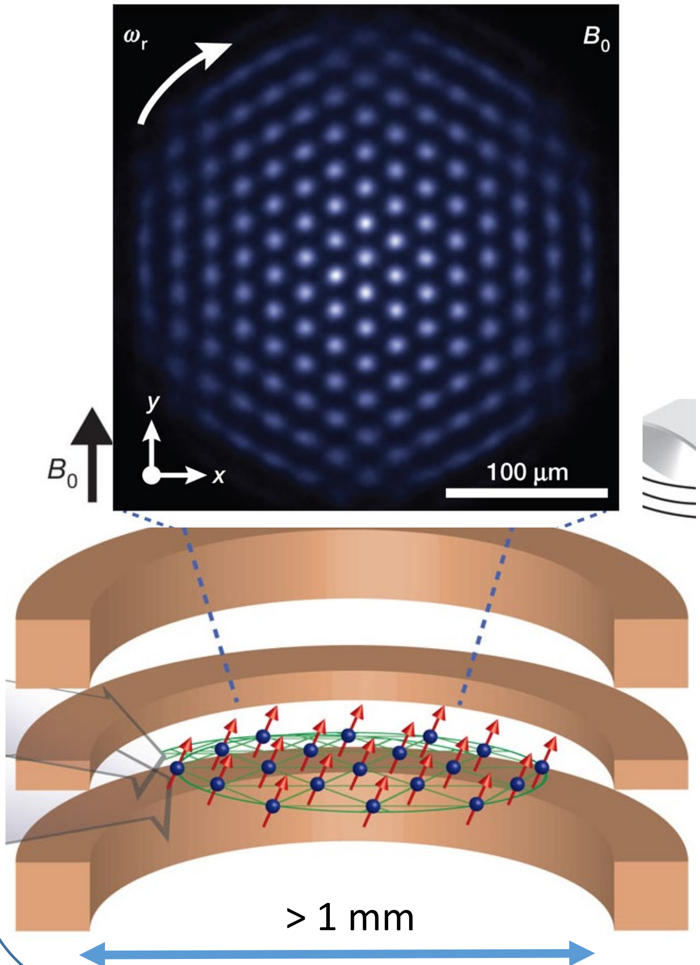
Tuneable range of interactions



Jurevic et al. Nature 511, 202 (2014)

2D ion crystals in macroscopic Penning traps

J. J. Bollinger, NIST



$$V_{\text{static}}(\mathbf{r}) + \{\mathbf{B}\}$$

Homogeneous magnetic field

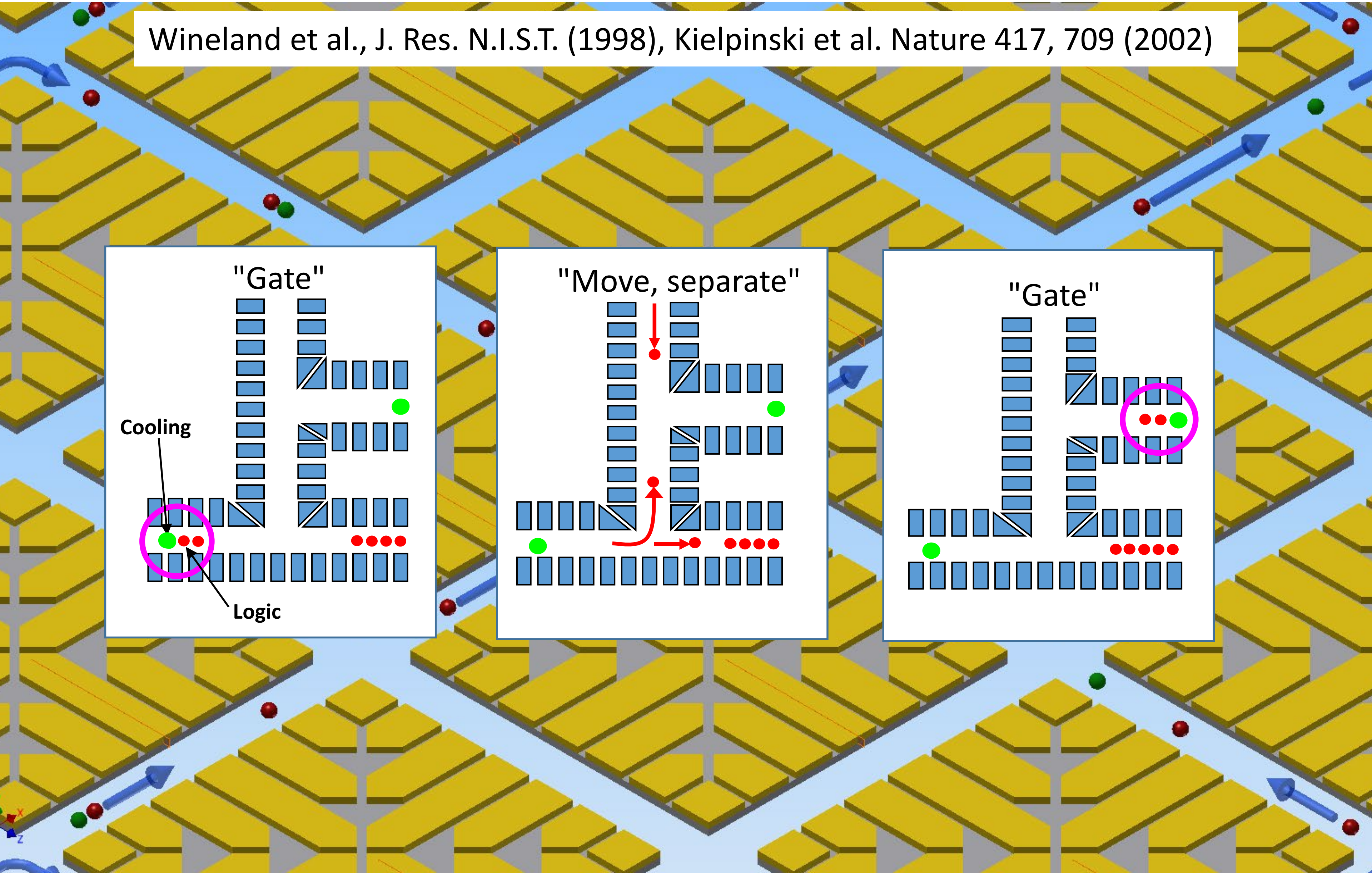
REPORT

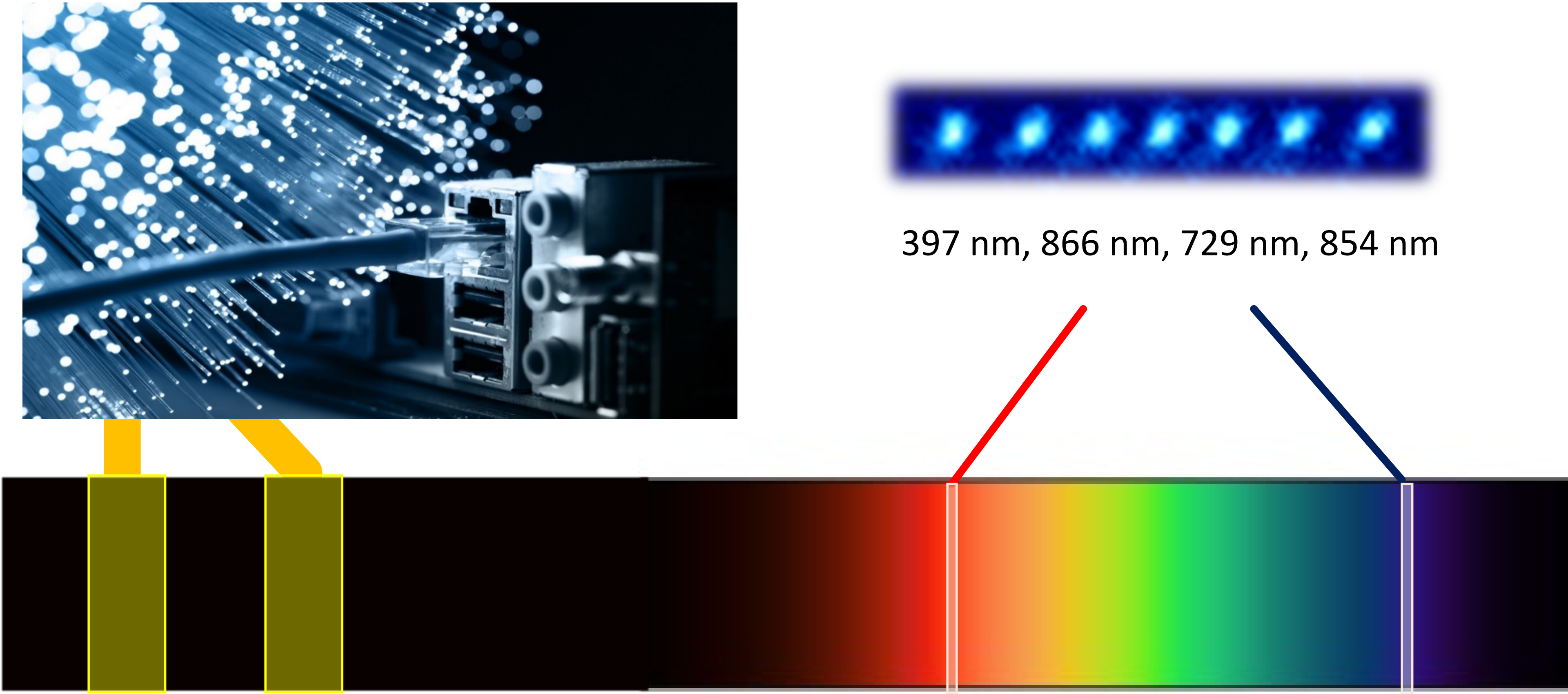
Quantum spin dynamics and entanglement generation with hundreds of trapped ions

Science 352, 6291 (2016)

The "Quantum CCD" architecture

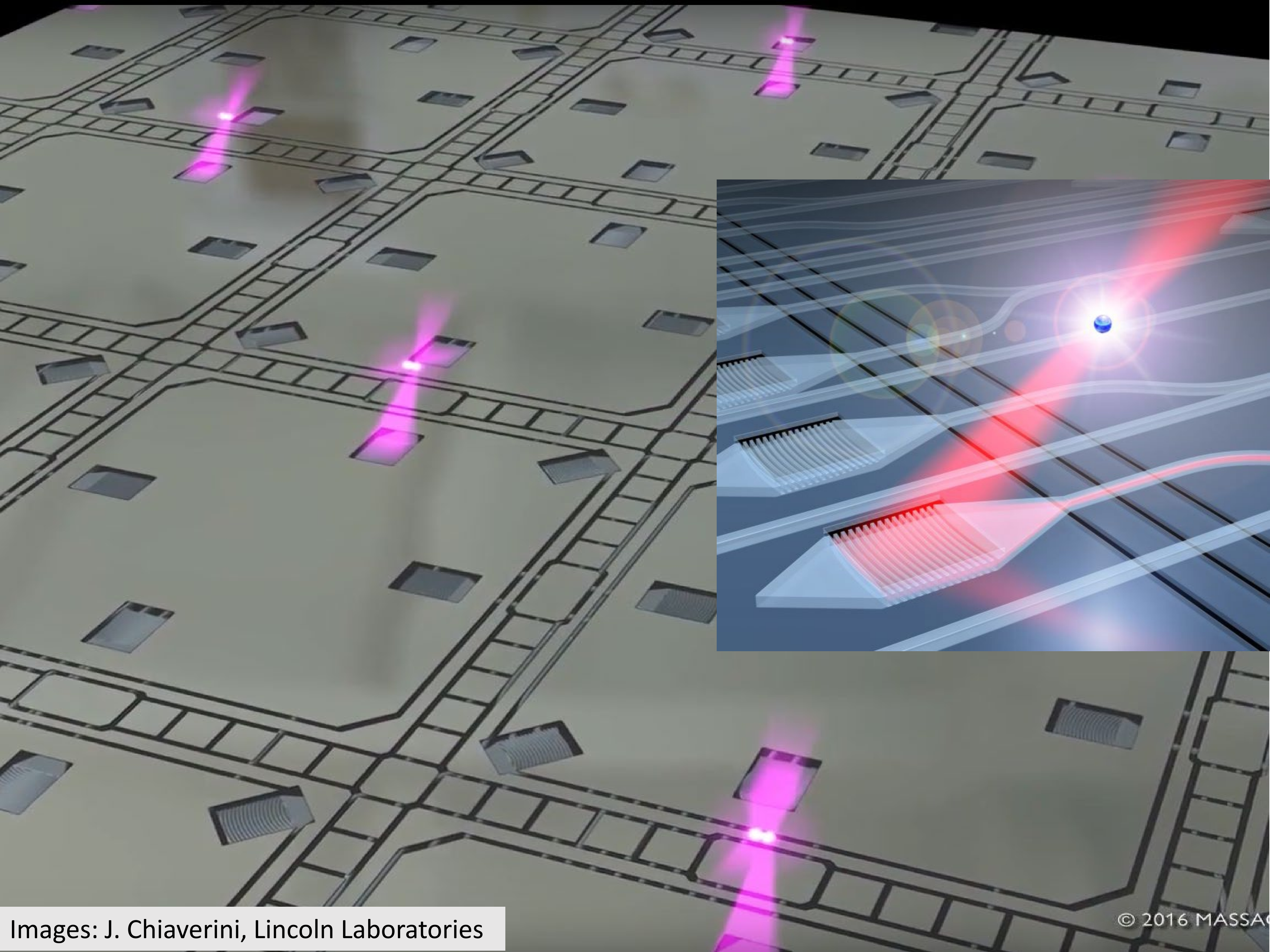
Wineland et al., J. Res. N.I.S.T. (1998), Kielpinski et al. Nature 417, 709 (2002)





On chip modulators
Input-output arrays
Plug and play fibre systems

Free-space bulky modulators (exceptions)
Self-developed UV fibres
Connectors home built



Images: J. Chiaverini, Lincoln Laboratories